# Robotised tangible user interface for multimodal interactions in virtual reality : anticipating intentions to physically encounter the user

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## ROBOTISED TANGIBLE USER INTERFACE
for Multimodal Interactions in Virtual Reality
Anticipating Intentions to Physically Encounter the User

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# Abstract


Virtual Reality (VR) experiences are by essence *multimodal*: they heavily rely on the users' senses. Yet, integrating Haptics - the sense of touch - in VR is a timely and challenging topic.
The goal of this thesis is to provide consistent *Haptic Feedback* while enabling intuitive *Interaction Techniques* in Virtual environments. More specifically, I aim to let the users perform **unencumbered interactions in VR** - where they are free of any contraption - and promote the design of a *Haptic Solution* in these regards.
To achieve this, I discriminate the Integration of Haptics in VR through a threefold approach:

1. I investigate how to provide believable fine tactile and large kinesthetic feedback;

2. I depict interaction techniques in VR, the tasks users perform and draw novel methods to enable them.

These enable me to draw an Analytical Framework with methodological contributions. This framework proposes novel dimensions to evaluate VR interactions via their associated Haptic Solutions, and emphasizes the promising future of *Encountered-Type of Haptic Displays*. It then depicts their specifications, challenges and opportunities from both conception and perception perspectives.

3. I then provide artefact contributions, and propose the conception and design of a **Robotised Tangible User Interface**, **CoVR**.

CoVR anticipates the users' intentions both *within-* and *between-objects*, to physically *encounter* the users at their *desired* object of interest *prior* to interaction. This thesis finally provides empirical contributions, with technical and perceptual studies around CoVR.



***Keywords:*** *Human-Computer Interaction (HCI); Virtual Reality; Haptics; Unencumbered Interactions; Encountered-type of Haptic Displays; Robotic Graphics.*

# Résumé

Les expériences en Réalité Virtuelle (RV) sont par essence *multimodales* : elles s'appuient sur les sens des utilisateurs. Néanmoins, l'intégration de l'Haptique - le sens du toucher - en RV reste complexe.
L'objectif de cette thèse est de prodiguer du Retour Haptique cohérent, en permettant des Techniques d'Interaction intuitives dans les environnements virtuels. Je vise à laisser les utilisateurs effectuer des interactions dites *"sans encombre"* en RV - où les utilisateurs ne portent aucun appareillage - et promeus à cet égard la conception d'une Solution Haptique. Pour ce faire, je distingue l'intégration de l'Haptique en RV selon une approche triple:

1. J'étudie comment prodiguer des retours tactile et kinesthésique vraisemblables ;
2. Je décris les techniques d'interaction en RV, les tâches exécutés par les utilisateurs, et conçois de nouvelles méthodes les permettant.

Je dérive ces deux premiers points pour apporter un Cadre d'Analyse avec des contributions méthodologiques. Je propose de nouvelles dimensions évaluant les interactions en RV via des solutions haptiques, et souligne le futur prometteur des Interfaces Haptiques à Contacts Intermittents. Je décris leurs spécifications, défis et opportunités - conceptuels et perceptuels.

3. Je contribue ensuite à la conception et l'implémentation d'un artefact : une Interface Tangible Robotisée, CoVR.

CoVR anticipe les intentions des utilisateurs intra- et inter-objets, et les encontre physiquement à l'objet d'intérêt de leur choix avant que l'interaction ne survienne. J'apporte enfin des contributions empiriques, via des évaluations techniques et d'usabilité de CoVR.

***Mots-Clés:*** *Interaction Humain-Machine (IHM) ; Réalité Virtuelle ; Haptique ; Interactions "sans encombre" ; Interfaces à Contacts Intermittents ; Robotic Graphics.*

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# List of Publications

### Articles in Peer-reviewed Conference Proceedings

– Elodie Bouzbib, Gilles Bailly, Sinan Haliyo, Pascal Frey.“ CoVR: A Large-Scale Force-Feedback Robotic Interface for Non-Deterministic Scenarios in VR.” In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST ’20).*
*Reference:* [Bouzbib et al., 2020]

– Elodie Bouzbib, Gilles Bailly, Sinan Haliyo, Pascal Frey. “ "Can I Touch This?" Survey of Virtual Reality Interactions via Haptic Solutions .” In *32ème conférence francophone sur l’Interaction Homme-Machine (IHM ’20’21).* Sous la dir. d’AFIHM, AFIHM. Metz, France: ACM, avril 2021.
*Reference:* [Bouzbib et al., 2021]

### Patent

– E.Bouzbib, G. Bailly, S. Haliyo, “System for Improved Interaction in a Virtual World” - *Application Number:* WO2021074530,
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### Articles in Reviewing Process

– Elodie Bouzbib, Gilles Bailly, “ Within-Object User Intention Prediction Model in Virtual Reality”
*Submitted September 2021*

– Elodie Bouzbib, Gilles Bailly, “ "Let’s Meet and Work it out": Understanding and Mitigating Encountered-Type of Haptic Devices Failure Modes in VR”
*Submitted September 2021*

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# Introduction

Virtual Reality (VR) is being used in an increasing number of fields such as training or simulation, which require a high level of realism. Virtual reality consists in creating a 3D artificial environment in which the user dives in. It aims at increasing presence, the feeling of being in another place than the one we are in. Presence heavily relies on the human senses, but at the moment, VR is largely focused on vision and auditory cues. Yet, presence can largely be increased through haptics - the sense of touch - providing further sensory information, involvement and control over the environment. In order to maximising this effect, natural interaction techniques with believable haptic feedback in VR [Magnenat-Thalmann et al., 2005] are currently investigated.

Integrating Haptics in VR globally aims to enrich the User Experience in VR. Haptics are more commonly provided through *ungrounded* solutions, such as controllers or wearables, which lack modularity but enable large displacements, or *grounded* solutions, which usually require the user to interact through the use of a proxy but can provide large kinesthetic feedback at an hand/arm-scale [Wang et al., 2020]. Both of these methods need users to hold continuously an interface in their palm, even when no interaction is required. An emerging and promising method consists in using robotised interfaces, encountering the users at their object location with an adequate haptic feedback, *only and only if* an interaction is required. These are anchored in the *Robotic Graphics* principle [McNeely, 1993], and enable what Krueger called *unencumbered interactions*[1] [Wexelblat, 1993].

[1] The user is *unencumbered* from any contraption of any form (controller, wearable, handheld etc), that are usually required to be continuously held/worn.

In these regards, I promote in this thesis unencumbered methods for providing haptics in VR. The global research question I address is: **How to provide natural interactions with consistent haptic feedback in unencumbered Virtual environments?** The difficulty for enabling haptics in VR relies on the multidimensional aspect of it. Haptics rely on both tactile (through the skin) and kinesthetic (tendons, muscles, proprioception) cues. Through tactile cues can be felt textures, temperatures, sliding, while kinesthetic cues feel forces, weight, compliance.

I propose along this dissertation to depict the integration of Haptics in VR through three distinct categories: (a) *Haptic Feedback*, being the various stimulated haptic cues and their intensity - on a user-perception perspective - (b) *Haptic Interactions techniques*, through the tasks users can perform and/or the methods enabling them, and finally with (c) a *Haptic Solution* perspective, which is hardware-based. These categories are not independent from each other and intrinsically linked, yet adopting a triangular approach around these three distinct categories enables to highlight their respective challenges and opportunities.

I therefore explore the challenges and opportunities according to these three categories and focus on the design, implementation and evaluation of robotised haptic interfaces in VR. My thesis is anchored in the HCI field, where we learn from the human modalities and design and evaluate interfaces around it.


Figure 1.1: (a) Interacting with an object in real life: through the objects' affordances - this teapot handle or base. (b) Interacting in VR: pushing a button.

## 1.1 Unencumbered Haptics in VR: Problem Statement

Krueger introduced a parallel between artificial and physical realities [Wexelblat, 1993], explaining how *"humans are mobile, not encumbered or tethered creatures"*, and concluded with an open question:

*"Is unencumbered artificial reality not possible?"*

Thirty years afterwards, this question still remains topical.

Virtual Reality currently aims to replicate real world visuals and interactions as seamlessly as possible. Yet, while a real-world user would manipulate an object through its affordances[2] (such as the teapot in Figure 1.1), a virtual-world user would need to access it through a controller and manipulate it by pushing a button.

[2] An affordance is a relationship between the properties of an object and the capabilities of a user that determine just how the object could possibly be used [Norman, 2013]

Controllers enable the user to have control over her environment [Mine et al., 1997]: (a) she can interact with **any** object and (b) is provided with vibrations/**haptic feedback** confirming her actions (Figure 1.2 - A).
An unencumbered interaction is therefore required to follow these criteria - all the objects of interest (a) must be **accessible** to interaction, and (b) must provide the user with a **haptic feedback** confirming the actions on the environment.

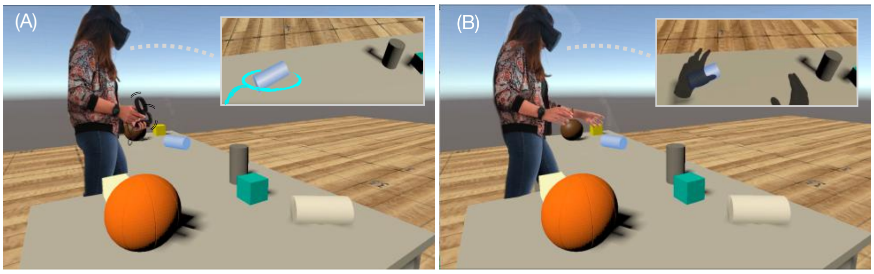



Figure 1.2: Interacting in the Virtual World: (A) With controllers; (B) With bare-Hands. Call-outs display the user view in the Head Mounted Display.

Unencumbered haptic interactions are intuitive, and should be enabled in VR (Figure 1.2 - B). This can be performed through robotised interfaces, encountering the unencumbered user with her adequate object of interest.
These interfaces theoretically enable various interactions and stimulate various haptic features, yet they raise two main challenges:

- *How to anticipate what the user wants to interact with?* (Figure 1.3 - A)
  Indeed, the uncertainty of the users' next intended interaction location requires the users intentions to be predicted.
- *How to provide the user with an adequate haptic feedback?* (Figure 1.3 - B)
  For the experience to be fully immersive and for the illusion of being in another environment to be complete, the user will expect a visuo-haptic consistency, ie a consistency between What she Sees and What she Feels (size, shape, texture, temperature, weight).

I focus in this dissertation on these interfaces, referred to as Encountered-Type of Haptic devices.


Figure 1.3: My approach is to (A) anticipate the users intentions, to (B) provide them with their object of interest. An interface could even reconfigure itself to (C) simulate the object of interest with similar haptic properties.

## 1.2 Research Approach

My main research approach is anchored in Interaction design as I design, implement and evaluate an *Encountered-type of Haptic device*[3]. The approach I promote is to take root from the real world human behaviour, from small-scale interactions (grasping and manipulating) to large-scale interactions (whole-body postures, leaning) to draw interaction techniques in VR, and design models and interfaces enabling them.

[3] As its name suggests it, it literally encounters the users at their object of interest.

I promote the use of my triangular approach to identify the questions raised for Enabling Haptics in Unencumbered VR:

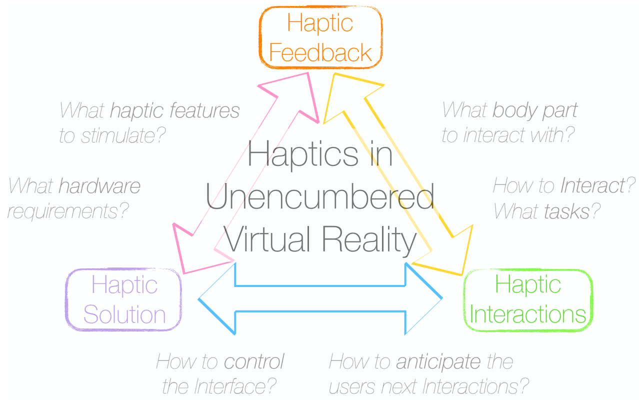



Figure 1.4: Problematics I explore in this thesis.

HAPTIC FEEDBACK *How to provide users with both fine tactile and large kinesthetic feedback?* On the one hand, hands interactions are important for manipulating objects or exploring small areas, hence I investigated *hand-scaled* interactions, and its associated *fine tactile feedback*. On the other hand, when a user discovers a *tangible virtual environment* to explore, one instinctive action would be to push on the worlds' limits, its walls, to check whether the feedback is consistent or not. This provides the user with *large kinesthetic feedback*. Therefore, I also analyse the integration of *whole-body* interactions.

HAPTIC INTERACTION TECHNIQUES *How to enable intuitive interaction techniques?* To understand how to enable intuitive unencumbered interactions in VR, I focus of the real world interactions to identify the tasks and opportunities users should be looking for in a VR experience. I also use these real world interactions (postures, gestures, manipulations) to extract information from the users' intent. My approach is then to draw novel interactions from these real world interactions, as well as to anticipate the users intentions to eventually physically provide them with their expected feedback from the virtual world.

HAPTIC SOLUTION *What are the hardware requirements for such an interface?* My aim is to identify and define the minimum requirements for an interface to safely, robustly and accurately reach the users' targets prior to interaction. Designing a robotised interface usually faces compromises and challenges: I identify them to design my haptic solution hardware specifications.

I conceptualize and design CoVR, a robotised interface enabling Unencumbered Haptic Interactions in VR. CoVR anticipates the users intentions, whether between multiple objects of interest or within a single one, to eventually physically overlay the users expected counterparts with real props. It provides both fine tactile and large kinesthetic feedback, and shows a great compromise between technical complexity and believable haptic feedback. We can imagine more complex interfaces as Future Work, as representation of the *Ultimate Display* [Sutherland, 1965], modifying their configuration (Figure 1.3 - C) to adapt to any Virtual *Matrix* the user would be in.

## *1.3 Research Domains*

This thesis is at the intersection of four research domains: HCI, Virtual Reality, Haptics, Robotics.

I adopt an **HCI** perspective and approach in this thesis: this community focuses on design, evaluation and implementation of interactive systems. My work transposes interaction paradigms from the real world to virtual ones, and I focus on designing and providing novel interaction techniques in VR through models and physical artefacts; to eventually enrich the user experience.

I address the question of enriching **VR** experiences. Research in Virtual Reality focuses on various areas: it primarily consists in creating immersive 3D artificial environments.It aims to improve presence through the integration of the user senses through hardware techniques, graphics rendering, or the reduction of cyber-sickness.

**Haptics** are commonly used to perceive feedback from our actions on the environment, and hence are a great mean for providing a control of our interactions in VR. The haptics community provides a better understanding of the sense of touch at physiological level [Andre et al., 2011, Gueorguiev et al., 2016, Adams et al., 2012] and how to simulate it [Hayward and Maclean, 2007, Hayward, 2011]. Nonetheless, haptics are generally not a dominant cue compared to vision, hence coupling Haptics with VR leads to an alteration of perception, for instance with different textures [Degraen et al., 2019] at a tactile level, or with *illusions* at a proprioceptive level [Abtahi and Follmer, 2018].

In order to let the users free of any contraption, I promote the use of a Robotised interface that physically encounters the user. Nonetheless, **Robotics** interfaces sharing space with users face multiple technical challenges (safety, speed, accuracy, robustness etc) on a designer perspective - which, when being solved, open up a wide range of interactions - on a user perspective.

## 1.4 Contributions of the Research

This thesis contains methodological, artefact, empirical contributions [Wobbrock and Kientz, 2016]:

*Methodological*

- I provide an analytical framework to analyse VR interactions via Haptic Solutions and emphasize the use of Robotic Graphics (robotised interfaces encountering the user), which show the best potential for providing consistent haptic feedback and natural interactions in VR.
- In the analytical framework, I also analyse Robotic Graphics interfaces by transposing a quality control process from industry product design (*FMEA*, Failure Modes and Effect Analysis) to research. It offers a better understanding of these interfaces conceptual and perceptual challenges, and highlights solutions mitigating them.
- I critically describe the current protocols for evaluating Haptics in VR, and propose various dimensions through my analytical framework as an alternative. I emphasize the use of my triangular approach (Haptic feedback, Haptic interaction techniques, and Haptic Solution) and the distinction between the user and the designer.

*Artefact*

- I describe CoVR - a robotised tangible user interface which enhances haptics in VR - through its conception, implementation and evaluation. CoVR lets the users unencumbered as it encounters them at their intended object of interest without requiring any held/worn contraption.
- As part of CoVR, I design two *software bricks* for Robotic Graphics interfaces: they provide a safe model to control these interfaces, and two users intention prediction models at different scales - *within* the object of interest and *between* objects of interest)[4]. Parameters can be tweaked, so these can be adjusted to other interfaces.
- I draw novel interaction techniques in VR using CoVR, for instance involving large force-feedback, transport and postures.

*Empirical*

- I empirically evaluate CoVR's intention models with various simulations, verifying their validity.
- I empirically evaluate CoVR's interaction techniques, both qualitatively and quantitatively.

[4] Anticipating the users intentions enables to physically overlay a virtual object and encounter the user prior to interaction.

## 1.5 Overview of the Thesis

**Part I** *Analytical Framework*
In this Part, I first provide background on Virtual Reality experiences, the integration of the senses for immersion and eventually, the integration of Haptics. This constitutes the basis for my thesis. I then provide a framework to analyse the existing work in Haptics and VR, and highlight the use of Robotised Interfaces to provide Haptic feedback in Virtual Reality experiences.

Chapter 2 *Haptics Integration in Virtual Reality Experiences*
This chapter introduces and positions my thesis. I discuss Haptics and VR definitions, use-cases and evaluations, to provide a better understanding of the goals and challenges of VR experiences using Haptics.

Chapter 3 *VR Interactions via Haptic Solutions*
In this chapter, I provide an analytical framework to depict VR interactions from both the user and designer perspectives. I distinguish the interaction types users can perform in VR, and describe their associated techniques. I depict and classify haptic technologies in VR according to two orthogonal axes (*degree of actuation* vs *degree of physicality*). I introduce the potentials of Robotic Graphics, which are then discussed in the subsequent chapter.

Chapter 4 *Robotic Graphics: Failure Mode Analysis*
This chapter focuses on Robotic Graphics technology. While their use is increasing, many challenges remain. We first analyse and highlight the conceptual challenges from a classic Robotic Graphics scenario, and discuss the different conception and perception failure modes. This chapter provides a framework of Robotic Graphics challenges and emphasizes their specifications and requirements on both the designer and user perspectives.

**Part II** *CoVR: Conception, Implementation, Evaluation*
In this second part, I use the specifications defined in the previous part to Conceive and Implement CoVR, an artefact enabling unencumbered haptic interactions in VR. I highlight a compromise in Robotic Graphics interfaces hardware capabilities and their associated software. I provide empirical evaluations of CoVR.

Chapter 5 *Within-Object User Intention Prediction Model*
In this chapter, I analyse the human reach-to-grasp behaviour and conceive a user intention model to anticipate the future users contact locations prior

to interactions (position-wise) and extract the local primitives (shape-wise), *within an object of interest*. This aims to be used as a software brick for Robotic Graphics implementations.

Chapter 6 *Robotised Interface Design and Between-Objects User Intention Prediction Model*
In this chapter, I present CoVR, a robotised interface providing large force-feedback in non-deterministic scenarios in VR. I couple hardware specifications with a *between objects of interest* intention algorithm.

Chapter 7 *Interaction Opportunities and Studies*
In this chapter, I present CoVR through its interaction opportunities. As opposed to the two previous design-oriented chapters, I here focus on the user perspective and evaluate CoVR through two user experiences.

**Part III** *Conclusions & Perspectives*

Chapter 8 *Conclusion*
This final chapter concludes this dissertation, summarizes the contributions and findings of my work. It also promotes the short and long term perspectives resulting from my findings.

# Part I

# Analytical Framework

2

# Haptics Integration in Virtual Reality Experiences

Perceiving another (virtual) reality can only be achieved through the involvement of several senses (multimodality). Vision is the first sense to be integrated in Virtual Reality, often coupled with auditory cues. Though, the human body is mainly sensitive to its environment through *proprioception*: the (in)conscient perception of our own body parts. For instance, any discrepancy between the human's visual perception and its body's proprioception would result in a discomfort because of a sensory conflict - these are known as *semantic violations*. These discrepancies violate the human body semantics and are heavily rejected by users [Rodriguez-Fornells, 2015]. Consequently, a computer generated Virtual Environment is required, by essence, to involve *multimodal* cues. This multimodality caters for the *plausibility of illusion* [Slater, 2009], the users ability to perceive that the virtual scenario is actually occurring. The challenges for this multimodality rely in the harmony of the senses integration, for the illusions not to break and consequently for semantic violations not to occur. Proprioception is considered to be amongst Haptics: the sense of touch. This sense can be stimulated by many more components, such as skin or muscles/tendons.

In this dissertation, I focus on integrating Haptics in Virtual Experiences. This is a "double or quits" challenge: while the aim is to improve the user experience, it can either achieve it *or* create semantic violations and create user discomfort. Also, *"improving"* is performed compared to a baseline, ideally using a referenced and rationalized evaluation protocol, which is currently lacking. In this chapter, I will hence position the thesis with definitions of Virtual Reality and Haptics, through their respective definitions and use-cases. I will then devote a section to their combination, Haptics and VR, where I will eventually raise evaluation protocols issues and provide guidelines.

## 2.1 Virtual Reality

Defining Virtual Reality can be seen from many perspectives: its concept, its methods, its interactions. In this section, I will first provide background on VR by introducing its origin story, and the current approaches for VR [Fuchs and Moreau, 2003]. I will then define the use-cases for VR - on a conceptual perspective - and how we evaluate an experience in VR - from a perceptual perspective.

### 2.1.1 Definitions

Virtual reality corresponds to a 3D artificial numeric environment in which users are immersed in [Jerald, 2015, McLellan, 2003, Wexelblat, 1993]. The virtual environment is created through the use of computer technology.

#### *Origins of VR: a idealized concept made come true*

Virtual environments have been speculated about for decades, as immersive multimodal worlds full of opportunities. One of the first models for Virtual Reality, the Sensorama [Heilig, 1962] was introduced in the early 60s (Figure 2.1-A), to enrich the users movie experiences, using vision, auditory, haptics and even olfactory cues. A few years later, Sutherland conceptualized the Ultimate Display:

> *"The ultimate display would, of course, be a room within which the computer can control the existence of matter [...] Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked.* [Sutherland, 1965]

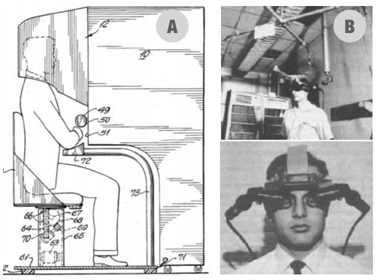


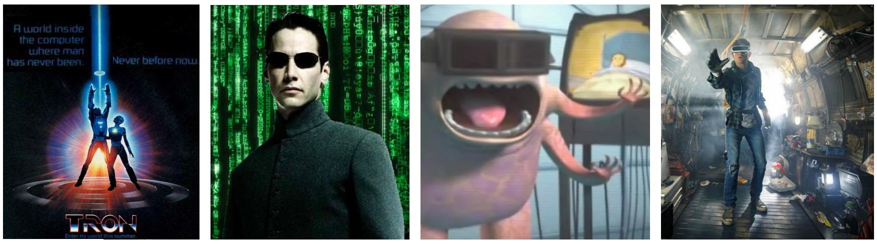

Figure 2.1: (A) *Sensorama device* [Heilig, 1962]; (B) Sutherland's *Sword of Damocles*.

Virtual reality's ambition was clear: providing a fully immersive journey in novel creative environments by involving all of the users' senses. Vision being the most dominant human cue, Sutherland then created the *Sword of Damocles* (Figure

2.1-B, as one of the firsts HMDs[1]. However, the concept being far beyond the 60s' graphics rendering capabilities, the project was given up on [McLellan, 2003].

[1] Head-Mounted Displays

Nonetheless, this abandonment did not stop the people from dreaming about what this technology could offer in many science-fiction interpretations (Figure 2.2), to an extent where even its boundaries even were explored. In these speculative futures, the characters can be skill-trained in the Virtual Environments (VE), or can be literally embodied and physically involved in these *Ultimate Displays*, to an extent where any mistake could actually impact their real bodies. This feeling of being in another place than the one we are physically in, with embodiment, involvement, and which provides the ability to learn skills, is called **presence** [Witmer and Singer, 1998]. Presence will be discussed later on, in Section 2.1.3.




*Tron*, 1982 *Matrix*, 1999 *Monsters, Inc.*, 2001 *Ready Player One*, 2018

Figure 2.2: Sci-Fi or Animation Movies exploring the Virtual Reality concept.

In the last decade, Virtual Reality has known a great evolution: computer graphics drastically evolved since the 60s, and the levels of immersion became quite convincing. Consequently, the technology that was once exclusively reserved to laboratories and research fields was democratized with affordable solutions from Oculus, HTC, Sony, Microsoft etc. Along with it, the research around this field keeps on expanding, with a novel generation of researchers who grew up with grand expectations over these sci-fi technologies. The current concepts for enabling VR and futuristic movies are nowadays converging, with dystopias looking more and more realistic. For instance, the latest VR adventure movie success, *Ready Player One* can easily be associated to a player with a classic HMD and an advance suit such as in Figure 2.10.

### *Current "Virtual Realities"*

The definitions of a virtual environment being quite broad, many concepts or even technical implementations are qualified as "Virtual Reality" [Fuchs and Moreau, 2003]. We will define the types of environment users can be provided with, as a function of the level of immersion they provide - *"the extent to which the actual system delivers a surrounding environment"* [Slater, 1999].

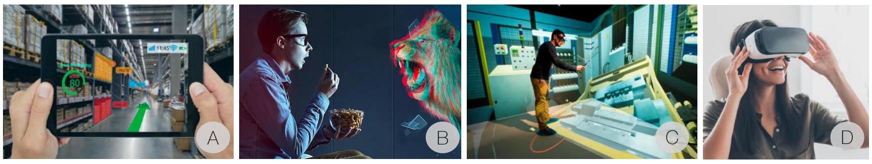



Figure 2.3: Current approaches for "Virtual Environments". A. Augmented Reality; B. Stereo Display; C. CAVE environment; D. Head-Mounted Display

*Augmented Environment* In an Augmented Reality (AR) environment, the users actually perceive the external world. However, its virtualization is through its augmentation: virtual props are overlaid on top of actual physical props. These "virtual artefacts" can only be used at a vision level. Indeed, as the user perceives the environment around him, the haptic properties of a virtual prop for instance cannot be perceived: the prop cannot physically be added. Though, using AR can be used for perceiving hidden properties or different cut sections of an element. The user can also choose to call-out some parts of his environment, or highlight them in different colors (Figure 2.4 - A). This augmented technology has mostly been made popular from the Google Glasses. This aims at providing further information on the environment but does not provide a sentiment of presence - as the user is not literally transported in another environment.

*Stereo display Environment* Stereo display does not rely on the physical environment such as AR. It exploits a screen (or more) where 2D images are displayed differently on the left and right eyes, for the users to perceive depth and hence a 3-dimensional view. This technique is most commonly known in the movie theatres - which enhance both vision and auditory cues but also haptics through actuated chairs [Park, 2011] (Figure 2.4 - B). The users can also be immersed through Simulation rooms: it consists of a combination of a physical environment and a virtual one. For instance, we can consider plane simulators, where the virtual environments provide a simulation of a flight while the users need to act on their environment using the same tools they would in a real environment.

*CAVE* "CAVE" is the acronym for Cave Automatic Virtual Environment. The environment is projected onto at least 3 distinct walls of a room-scale arena (Figure 2.4 - C). The environment being fully computer generated - as opposed to the Augmented reality which exploits the physical environment. In such environments, the users still perceive their own body as a part of the environment.

*HMD-VE* In an HMD VE - Head mounted display (Figure 2.4 - D) Virtual Environment, the outside world is not noticeable; the users are *fully* immersed. For the users to perceive a body part, they would hence require avatar representations. When the graphics rendering are consistent, this consequently provides a high level of presence - the user's vision shows him a different environment than the one he is physically in.

> In this dissertation, I only consider a virtual reality with a Head-Mounted Display. The users are fully immersed and do not perceive either the environment or their real body. As they do not notice any artefacts or movements around them, this provides VR designers with the opportunity of modifying the physical world. Moreover, this unawareness of the real environment changes allows for many illusions around the users perception, even at a proprioceptive level.

### *2.1.2 Using VR: Combining Intrisic Functions*

Virtual reality offers novel opportunities in many fields. The advantages are within all the "changes" it is able to provide. In the following chart (translated from the French [Fuchs and Moreau, 2003]), we can indeed discriminate the intrisic functions of VR (Figure 2.4):

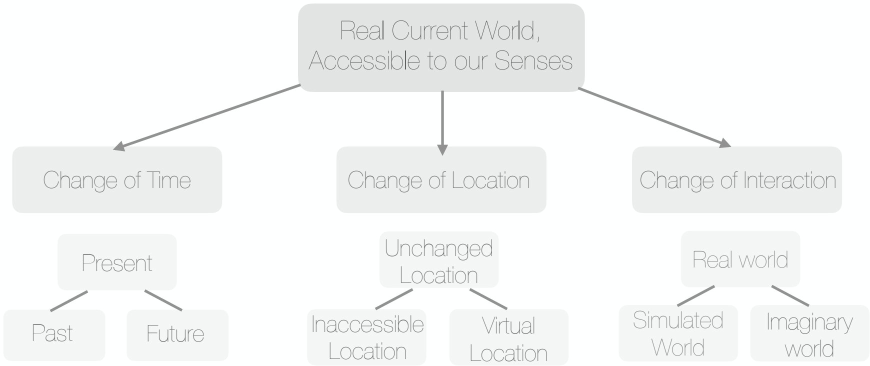



Figure 2.4: Intrisic Functions of VR from [Fuchs and Moreau, 2003].

Combining these different functions (time, location, interaction) result in a wide variety of use-cases, which are described in the following non-exhaustive list, fixing their **change of interaction**[2].

[2] As a side note, these use-cases all can be augmented using Haptics, which will be evoked later on, showing its benefits for them.

#### *Simulated World Use-Cases*

A "present time" **simulated world** would benefit use-cases such as skill-training (industry, surgery, dentist, rehabilitation, army, medical, safety, tool-training); where VR aims at transferring a known-hows to the real world, without any loss material cost. A simulated world can also allow users to remotely work together in a work-like environment or board room. It can also allow for a complete change of scale: in either touristic or architectural views, the user can be enlarged to have a more global view of his environment; in biology, the user can be reduced to a microscopic view to perceive another scale constraints. This can also be helpful in CAD designs, where the user can have a better perspective of his conception work, or in realestate, where we can virtually visit and decorate a potential apartment of interest. It could also provide the users with "inaccessible locations", such as archaeological or historic sites; and even simulate them at a different time (in the past, for a *realistic* reconstitution). This literal *realism* can also be exploited to help recovering from traumas: VR is currently being used in treatments of phobias, autism, anxiousness etc [Klinger, 2006].

#### *Imaginary World Use-Cases*

On the contrary, an **imaginary world** can focus on more "abstracted" use-cases. For instance, a user can navigate through data of various visualisations; or play in a surreal and futuristic science-fiction environment, where he could embody any form and achieve unrealistic goals. In these last cases, the users are still fully immersed and perceive a believable environment: this shows the importance of the term *plausible*, as opposed to *realistic*. This leads us to the different evaluation protocols in VR.

### *2.1.3 Virtual Experiences Evaluation Protocols*

Evaluating Virtual experiences is difficult, as it needs to take into consideration many parameters: from the users personalities, to the interface usability [Slater, 2009], through the conditions in which the evaluation is provided (eg in the virtual environment or in the real environment) [Schwind et al., 2019].

The most common way to measure the efficiency of a VR experience is through *presence*. Presence is defined as the "subjective experience of being in one place, even when one is physically situated in another" [Witmer and Singer, 1998]: it consists in a blend of user involvement and user immersion - and corresponds to perceiving a whole another world in which we dive in. It is also referred to as *the place of illusion* [Slater, 1999, Berkman and Akan, 2019]:

> *"It is a perceptual but not a cognitive illusion, where the perceptual system, for example, identifies a threat (a precipice) and the brain-body system automatically and rapidly reacts (this is the safe thing to do), while the cognitive system relatively slowly catches up and concludes 'But I know that this isn't real'. But by then it is too late, the reactions have already occurred.*" [Slater, 2018]

Therefore, it can be expressed as a combination of physiological factors (heart rate [Insko, 2001, Lepecq et al., 2008], sweat etc), or more commonly, quantified through more rationalized questionnaires.

### *Presence Factors*

Presence can be defined by various relative factors that designers can select (eg physiological), or quantified using a referenced evaluation protocol. By definition, presence requires *involvement* and *immersion*. Involvement is a consequence of focusing one's energy and attention on a coherent set of stimuli; while immersion consists of perceiving oneself enveloped by and interacting with an environment that provides a continuous stream of stimuli.

Sheridan defined presence through three factors: *extent of sensory information, control from our senses on the environment, ability to modify physical environment* [Sheridan, 1992]. Witmer refined this definition and how to quantify it, through four major factors: 1) Control, 2) Sensory, 3) Distraction and 4) Realism factors [Held and Durlach, 1992].

*Control* Control factors consist of evaluating the immediacy of control (eg when the user acts, the environment must react), anticipation (eg ability to predict the consequences of an action), and the ability to modify the environment (eg through manipulation tasks etc).

*Sensory* Sensory factors imply the multimodality of the experience, the environmental richness and multimodal presentation. Yet, quantifying "sensory factors" at the moment heavily relies on graphics and interface rendering quality. The interface quality is a viable factor for evaluating the environment - for more precise use-cases evaluations such as avatar representations, the experience quality can be quantified through standardized avatar embodiment/body ownership questionnaires [Gonzalez-Franco and Peck, 2018].

*Distraction* While sensory and control factors should be maximised, distraction factors should be diminished. Indeed, the more isolated from outside distractions the user is, the better presence is.

*Realism* As previously mentioned, the term *realism* remains difficult to use. These factors involve the consistency of the virtual world and its plausibility, but also how much disorientation the user feels after his experience. The more disoriented in the real world after an experience, the better presence is.

After a Virtual experience, users are asked to fill in presence questionnaires, by rating their experience on Likert scales[3]. Nonetheless, presence results can vary as a function of the protocols in which the questionnaires are taken in. For instance, according to recent studies, presence results are higher when fill directly in the virtual environment [Putze et al., 2020, Schwind et al., 2019]. As mentioned by Witmer, these results are also a function of the users personalities.

[3] The questions belong to either of these factors, and their answers quantify the quality of the experience.

### *Personality Factors*

*Immersive Tendency* Prior to a VR experience are usually taken Immersive Tendency questionnaires (ITQ). They consist in evaluating the users personalities through their tendency to become involved in activities, to play video games, to maintain focus on current activities, or even calls out the users hobbies, or their creative and imaginative sides. To simplify it, a user with a tendency to daydream, a great involvement in dreams/hobbies and a great ability to focus (eg blocking out distractions when involved in a task) would probably have greater presence results that a "cynical" users with a low capacity to involve themselves in a task.

*Simulator Sickness* In the personality factors, and tied to a user's immersive tendency results, we also have Simulator Sickness Questionnaires (SSQ). Immersive simulation technologies knew a growth in the 90s, while latency and graphics rendering were still quite low (compared to our current technologies). In these regards, evaluations started to look at quantifying the motion sickness generated on the users, to better identify the gaps in the technology [Kennedy et al., 1993]. Virtual reality obviously faces the same issues. Presence does focus on quantifying the visual experience quite well, though it does not enable to quantify the integration quality of proprioception, balance, or any discrepancy between what the users see and what they should feel. These potential disorientation or nauseas are hence identified with Virtual Reality Sickness Questionnaires [Kim et al., 2018, Bimberg et al., 2020] (VRSQ).

### *Critics of Questionnaires*

Slater provided a response to Witmer and Singer's questionnaire [Slater, 1999], arguing that its usability was questionable and that the ITQ questionnaire would be more appropriate to investigate the people's reactions in VR. The questionnaire being tech and graphics oriented, he concluded that "no one would really want to use this questionnaire", but because of a lack of options in this field, we did not have much choice but to use it by default. He then provided his own presence questionnaire [Slater and Steed, 2000, Usoh et al., 2000] (second most used presence questionnaire according to [Schwind et al., 2019]), focusing on the simulated/virtual environment and the users' involvement.

In the same regards, I believe that current presence questionnaires are quite outdated, and focusing on the technology that was available decades ago. On the opposite, ITQ can be seen as a good questionnaire to anticipate one's reaction prior to an experiment, though we yet do not know how to exploit it properly. These evaluation protocols do need to be renewed and standardised, to focus on the challenges VR is currently confronting. Indeed, as a catch-22, they are still being more and more used, primarily because nothing else is available yet. Questionnaires however show a real potential to extract empirical information from an experience: physiological factors for instance (such as sweat or heart rate) would require specific sensors. Their output is easy to quantify, but this hardware requirement can limit the replicability of the experiment. Empirical studies through questionnaires for VR experiences have the advantage to be accessible and replicable. A novel rationalized questionnaire for instance would integrate both presence, embodiment, sickness, immersion tendency and the harmony in the integration of other cues (than vision). Papers such as [Lin et al., 2002] manage to regroup many different evaluation protocols for a thorough evaluation of their technology (field of view in this case) - using presence, enjoyment, memory, SSQ - but few research papers provide this level of details.

## 2.2 Haptics: the Sense of Touch

Haptics is the general term for the sense of touch. Haptics is perceived through the skin - the largest human organ - but also through muscles, tendons, and proprioception. Similarly to the previous section, I will define Haptics in general, and then its current exploitation for different use-cases and their associated evaluation methods.

### 2.2.1 Definitions

The sense of touch is often underestimated. We can imagine people who do not hear (deaf), see (blind) or smell, though we have a hard time imagining someone who would grasp an object without perceiving any feedback. Haptics is a combination of two types of cues: *tactile* and *kinesthetic*.

#### Tactile cues

Tactile cues are developed through the skin. The skin is composed of four types of mechanoreceptors [Lederman and Klatzky, 2009] (see Figure 2.5). When touch is performed, they are structurally deformed and provide a feedback.

- *Merkel nerve endings:* These mechanoreceptors transmit mechanical pressure, position and shapes or edges. They are more densely found in the fingertips and lips. Merkel's disks are small, which enable them to provide localized stimuli.

- *Ruffini corpsucle end-organ:* Ruffini endings are sensitive to skin stretch and provide both pressure and slippage information. They contribute to proprioception and kinesthesia as they provide feedback for gripping and controlling fingers positions and displacements.

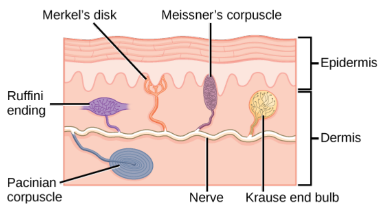



Figure 2.5: Schematic Cut Section of the Skin [noa, 2018]: Four types mechanoreceptors (Merkel, Ruffini, Pacinian, Meissner) are located within the epidermis and the dermis, along with thermoreceptors (Ruffini, Krause).

- *Pacinian corpuscles:* They are sensitive to high-frequency vibration and pressure. When they are compressed, this stimulates their internal configurations, which provides this information.
- *Meissner's corpuscles:* These are highly sensitive and provide light touch and vibrations information. They are also referred to as *tactile corpuscles*, and are responsive to fine details. Similarly to the Merkel nerve endings, these are primarily located in the fingertips.

The skin also contains thermoreceptors, which transmit information about temperature: the Ruffini endings respond to warmth, while the Krause ones detect cold. Through tactile cues, the human can hence feel shapes or edges, pressure, vibrations or temperature changes.

### *Kinesthetic cues*

The kinesthetic cues rely on proprioception, *the perception and the awareness of our own body parts positions and movements*. Mechanoreceptors into the muscles, the "spindles", communicate to the nervous system information the forces muscle generate, as well as their length change [Jones, 2000]. The primary type of spindle is sensitive to the velocity and acceleration of a muscle contraction or limb movement, while the second type provides information about static muscle length or limb positions. Kinesthetic cues hence allow to feel forces, as well as perceiving weights or inertia. They are also involved in every single posture a human can perform, through proprioception and balance.

### *Haptic Features Summary*

All of these *haptic features*, when combined, enable the discrimination of many properties from the outside world: textures, shapes, temperatures, weights etc. Haptics are being used in every task we perform on the outside world: walking, manipulating an object, hugging a friend. Though skin, muscles and tendons are across our whole body, some body parts are still more sensitive than others. Penfield proposed a representation of this phenomenon, called the *Homonculus* (Figure 2.6). In this figure, every body part size is proportional to its global sensitivity.

Figure 2.6: Penfield's Homonculus. All human body parts' sizes are proportional to their global sensitivity.

### 2.2.2 *Using Haptics: Stimulation vs Simulation*

Haptics, as *sense of touch*, is stimulated whenever in contact with any tangible interface. It is constantly being used in everyday's lives: our postures, our balance, every single *physical* interaction - with any form of *physical contact* - performed on an object or another human being is going through our haptic cues. Yet, haptics is still leveraged in many use-cases, where it is specifically artificially stimulated. Haptics, as *the science of touch*, consists in understanding the sense and its perception, but also in the replication of haptic feedback through this artificial stimulation.

#### *Stimulating Haptics: Perceiving Touch Interactions*

Stimulating Haptics is done when touching and being touched, typically whenever our sense of touch is involved. The most common example of haptics being stimulated is for communicating with blind people: the Braille language was created as a "touch" alphabet, making visual artefacts tangible and physically accessible for the visual-impaired. Similarly, their canes enable to explore the whereabouts through haptics: it informs the user of a potential physical collision with the environment.

Overall, haptics are known to communicate: it provides information from the environment, acting as both transmitter and receiver - it touches, and reciprocally is being touched.

#### *Simulating Haptic Features: Replicating Touch Interactions*

I define the Simulation of Haptic features as the *superficial replication of external features to enhance the users' sense of touch*. Both Tactile and Kinesthetic cues can be simulated: for instance, vibrations between 80 to 400 Hz are felt through the skin, which can be *superficially* exploited for users to perceive stickiness, smoothness, pleasure, vibration or friction (eg Surface haptic displays [Bau et al., 2010]), or even to explore a 3D terrain or volumetric data [Sinclair et al., 2014].

Similarly, kinesthetic cues can be *superficially* stimulated: EMS (Electro-muscle stimulation) replicates the electric signals from the brain, and *superficially* enables the contraction of the users muscles, for them to learn gestures [Lopes et al., 2015] or to perceive kinesthetic feedback [Lopes et al., 2015].

Simulating simultaneously both of the tactile and kinesthetic cues can even be leveraged to convey different user emotions through touch [Teyssier et al., 2020].

### 2.2.3 Haptics Evaluation Protocols

Many Hapticians[4] actually refer to different implicit "Haptic categories" using the term *Haptics* - I identify and analyse these categories. As I mentioned it in the Introductory chapter, I discriminate Haptics - as the science of touch - in three intrinsically linked categories: Haptic Feedback, Haptic Interaction techniques, and Haptic Solution. I insist on distinguishing these categories as their content *(what?)* and respective evaluation methods *(how?)* are different.

[4] Haptic Specialists or Designers

With the growth of the interest for haptics and its associated technologies, Kim and Schneider recently designed a novel framework to evaluate haptic feedback: the *Haptic Experience* [Kim and Schneider, 2020]. In this section, I extract the definitions from the "Haptic Experience" to position, justify and strengthen my classification.

*Haptic Feedback* As previously seen with the *Homonculus*, sensitivity varies depending on body parts. Though, it also varies from one individual to another.

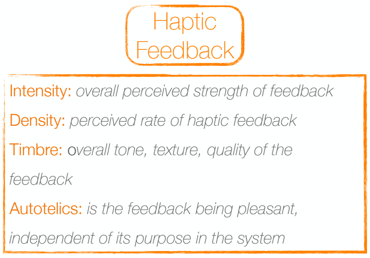



Figure 2.7: Definitions of some types of Haptic Feedback Evaluation questions.

*What?* Haptic feedback evaluates the user perception, and qualifies the previous haptic features (slippage, friction, textures, temperature, weight, shape discrimination). Their evaluation can be regarding their intensity, density, timbre and autotelics (see Definitions in Figure 2.7).

*How?* Evaluating Haptic feedback is hence usually performed through empirical studies. Many of these studies measure a stimuli *Just Noticeable Difference* (JND) over a panel of users [Matsuoka et al., 2002, Tinguy et al., 2019]. This JND is defined by dichotomy, and represents the required thresholds for a majority of users to perceive the said- stimuli. This JND hence quantifies the user perception.

*Haptic Interaction Techniques* This category is related to the global haptic interactive experience. It hence makes more sense to evaluate it when Haptics is coupled with other cues, such as vision (eg. subsequent section)[5].

[5] The term "Interaction techniques" used here is to dissociate from the 3D Interaction techniques proposed by Bowman et al. [Bowman et al., 2001]. This category is with a haptic perspective.

*What?* This category relies in-between the Haptic Feedback and its associated Solution: it reflects the quality of the global interaction and how the interaction is enabled. The idea is to understand how the interaction is provided, whether the interaction seemed "natural", if it was correctly integrated with other sensory cues, both temporally and with harmony.

*How?* Interaction techniques are principally evaluated empirically. It addresses many questions, which definitions are in the figure below (Figure 2.8).

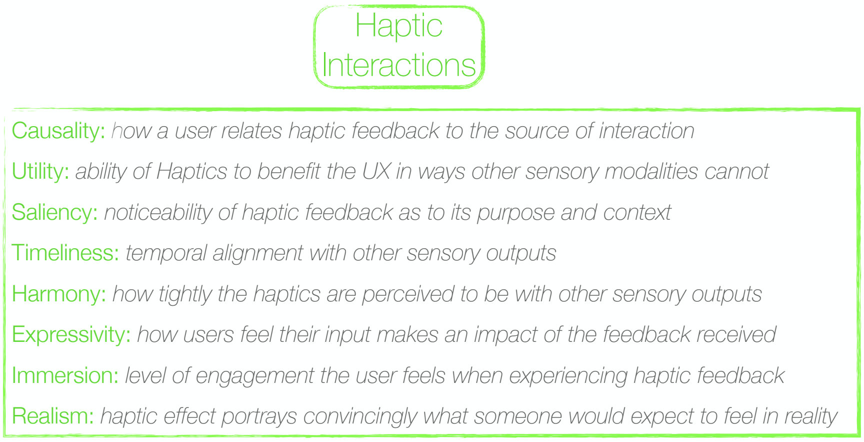



Figure 2.8: Definitions of some types of Haptic Interaction techniques Evaluation questions ("Haptic Interactions" label refers to "Haptic Interaction Techniques").

*Haptic Solution* This category is device and hardware-based.

*What?* Many haptic designers only consider technical specifications to quantify their rendering quality, for instance to quantify a device's haptic transparency [Hayward and Maclean, 2007] or more notably for force-feedback. This is a practical approach as it does not rely on users, but on mechanical specifications: it is easier and reliable to compare mechanical solutions through the force they provide than using a user perceptual study.

*How?* For instance, *Haptipedia* [Seifi et al., 2019] is a haptic solution database for Hapticians. It classifies them through their workspace and mechanical capabilities such as their translational forces and rotational torques. Technical questions such as Timeliness (system latency), Consistency (system repeatability) and Density (system frame rate) can also easily be quantified (see Figure 2.9).

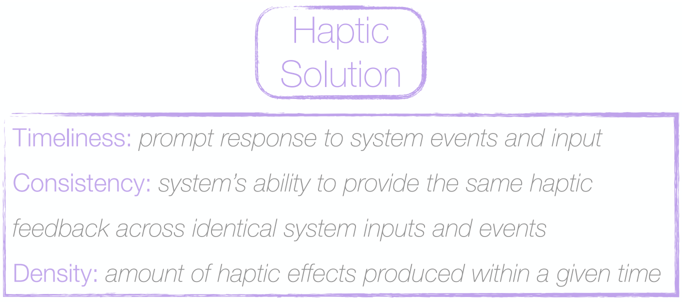



Figure 2.9: Definitions of some types of Haptic Solution Evaluation questions.

## 2.3 Haptics and VR: enriching the Virtual experience

From the multimodal aspect of VR interactions, Haptics shows the potential to enrich the VR experiences. This section depicts the advantages of coupling Haptics and VR, analyses its use-cases and depicts three categories to evaluate it.

### 2.3.1 Haptics and Vision in VR

*Visual Dominance over Haptics*

Vision is a dominant cue compared to Haptics: we tend to trust more our vision than our haptic feedback. This phenomenon is known as *vision capture* [Ernst and Banks, 2001]. Hence, combining the VR capabilities to Haptics provides a novel framework to understand haptic perception and sensitivity [Pusch and Lécuyer, 2011]. From the previous definition of *Semantic violation*[6], the limits of the brain in terms of visuo-haptic discrepancy is for instance largely studied in VR [Cheng et al., 2017, Bergström et al., 2019].

[6] Discrepancies between different user cues (here vision and haptics) which violate the human body semantics and are heavily rejected by users.

Vision can then be leveraged over haptics, to trick users into perceiving many different features - such as weight [Rietzler et al., 2018, Samad et al., 2019], stiffness [Heo et al., 2019, Lecuyer et al., 2000], textures [Zenner and Kruger, 2019] - while enabling designers to provide interactions without putting too much effort on physical interfaces' modularity. Indeed, these *pseudo* haptic features are performed software-wise as they mostly rely on altering graphics rendering. A simple alteration of the users' hands speed can already provoke a stiffness or weight change perception.

In the same regards, visuo-proprioceptive illusions are often studied in VR [Azmandian et al., 2016, Kohli, 2010]: the users embodiment into their avatars allows for the *redirection* of the avatar body parts, which causes an imperceptible alteration of the users real displacements.

*Haptics Contributions to Vision*

Haptics however play a fundamental role when added to vision. First, providing a haptic feedback whenever an action is performed provides the user with *control* over his environment (which is a main factor in the presence definition) [Mine et al., 1997, Held and Durlach, 1992]. It confirms the users actions, and enables to understand the environment constrains for interactions. Perception-wise, it was even shown to enable a better estimation of depth [Makin et al., 2019] and more believable environments [Magnenat-Thalmann et al., 2005].

Many research look for "intuitive" 3D interactions in VR [Poupyrev et al., 1997, 1996]. However, if these interactions were providing an adequate haptic feedback, they would indeed be more intuitive and would not require any training or tutorial to be used [Mine et al., 1997]. In these regards, [Hinckley, 1994] demonstrated how providing users with haptic feedback enabled them to understand their manipulated interface and its associated interaction technique without training: being physically constrained through Haptics enables this understanding.

Perceiving (avatar) hands - to be embodied in - decreases the user's cognitive load [Hinckley et al., 1997]. Furthermore, integrating haptics in VR provides a physical presence which increases immersion [Lepecq et al., 2008]. At an emotional and physiological scale, the heart rate of a user can literally increase with the use of haptics through real objects [Insko, 2001]. As vision aims to provide information on the environment, haptics actually completes it.

### 2.3.2 *Usability and Benefits of Haptics & VR*

This complementarity of Haptics with Vision is used in many different use-cases, which can be extracted from the VR ones (Section 2.1.2). Training in VR is one of the fields Haptics impact the most: indeed, the lack of tutorial when an adequate haptic feedback is to be provided is a great advance in industry [Poyade et al., 2012], that decreases the costs in lost materials for instance. It also helps understanding the "correct" gesture at a proprioceptive level [Gutierrez et al., 2010, Villegas et al., 2020], with a correct skill transfer from VR to reality. This can be used for machinery training [Cao et al., 2020] or maintenance cases [Winther et al., 2020]. The addition of haptics in training virtual environments also contributes to medical applications [Escobar-Castillejos et al., 2016, Ullrich, 2012], such as laparoscopy training [Zhou et al., 2012], needle insertion [Corrêa et al., 2019], or with dental education - where real jaws are substituted with props and an a texture feedback is simulated within the tools [Konukseven et al., 2010, Kim and Park, 2006].

Moreover, fields such as archaeology benefited from haptic feedback. With the growth of virtual reconstitution, retrieving the haptic textures from digitalized physical parts enables to assemble them with a precision that vision itself does not allow [Nicolas et al., 2015].

Finally, in gaming, the growth of "at-home" technology enables a full user immersion. For instance, the *TeslaSuit* (Figure 2.10) [VRElectronicsLtd, 2019] provides a full body tracking for avatar embodiment, with information on the environment temperature and force-feedback from its constraints.


Figure 2.10: *TeslaSuit* [VRElectronicsLtd, 2019].

### 2.3.3 Evaluating Haptics in Virtual Environments

Many surveys actually compare haptic solutions or haptic feedback in VR. After analysing the dimensions they investigate, I propose here again to discriminate this "Haptic Evaluation in VR" using the three previously depicted categories: Haptic Feedback, Haptic Interaction techniques, and Haptic Solution[7].

[7] Note that the definitions in Section 2.2.3 are still valid here, as we still refer to a Haptic Experience.

- *Haptic Feedback:* This category is focused on "pure Haptics", on a user perception-side. This is user-centered but heavily correlated to the design parameters. It couples the previous "Haptic feedback" category content (Section 2.2.3) with visual renderings, eg it measures its consistency compared to the users' visual expectations. It regroups the types of feedback that can be provided, from tactile cues (eg textures, friction) to kinesthetic feedback (eg forces) [Wang et al., 2020, Dominjon et al., 2007].

- *Haptic Interaction Techniques:* This category corresponds to the evaluation of the interaction "plausability", its intuitiveness, and the amount of control the users are provided with. It is user-centered and highly depends on the use-cases, the tasks a user is able to perform in the Virtual environment, or the body parts it involves (fingers, hand). While interacting with a virtual environment with our bare-hands seems intuitive, haptic interaction techniques consisting in providing the user with haptic solutions that need to be held continuously would make sense for training tasks. In the same regards, comparing an interaction consistency varies on this use-case. For instance, the haptic benefits for medical or industrial assembly training can be evaluated against a real experience condition [Poyade et al., 2012], with criteria such as completion time, number of errors, user cognitive load [Gutierrez et al., 2010]. On the opposite, the haptic benefits for a gaming experience are more likely to be evaluated through immersion and presence, comparing "with/without haptics" conditions [Cheng et al., 2015] and the interaction opportunities the user could perform.

- *Haptic Solution:* This category is actually more engineering and design-based: it consists in evaluating a mechanical/robotics solution [Rakkolainen et al., 2020, Talvas et al., 2014, Hayward and Maclean, 2007]. In [Dominjon et al., 2007], solutions are evaluated as per their robustness, ease-of-use and safety. Similar features would include their speed and accuracy, their "scalability" and applications [Wang et al., 2019] (for deployment purposes, which can also be interpreted as ease-of-use), or the use of an operator to make it functional.

These categories are obviously linked: they will for instance be used in the next chapter, differentiating *Haptic Solutions* depending on the enabled *Haptic Interaction Techniques* and the *Haptic Feedback* being provided.

> Haptics is a complex sense, as it involves many different features to stimulate. Integrating Haptics in VR shows a great potential to enrich the user experience, as it supposedly increases *presence*, through an improved users immersion, involvement and plausibility of interaction. When evaluating Haptics and more specifically Haptics in VR, we need to differentiate the different approaches that are available: through pure *Haptic Feedback* (eg textures, slippage, weight), *Haptic Interaction Techniques* (eg controllers/bare hands), or *Haptic Solutions* (eg mechanical/robotics features).

## *2.4 Conclusion*

Virtual Reality is by essence *multimodal*, though the integration of haptic feedback has not been convincing yet and it remains a timely topic. This is justified through the multi-faceted aspect of haptics, the sense of touch.

Sutherland's *Ultimate Display* is still far from being conceived: many solutions are currently developed towards the enhancement of Haptics in VR, yet as many surveys show it, different mechanical capabilities provide different haptic features stimulation through different interaction techniques and gestures [Wang et al., 2020]. This is also introduced from the three categories I define and promote in this dissertation: Haptic Feedback, Haptic Interaction techniques, Haptic Solution.

This Chapter provided a background and definitions for VR and Haptics. In the rest of this dissertation, only VR through a HMD will be used - the user is not able to perceive his real environment. I however do not restrain my research to a single haptic feature: my aim is to take root from its multi-faceted aspect to design a modular, intuitive interface for plausible experiences.

WHAT YOU MUST REMEMBER

*Positioning:*

- Integrating Haptics in VR is a "double or quits" challenge: it can either drastically enhance the experience *or* create a semantic violation due to inconsistencies with visual renderings.
- Understanding the challenges of Haptic Integration in VR is complicated due to a lack of referenced evaluation protocols.
- Still, enhancing Haptics in VR should drastically enrich the User experience due to the Virtual Reality Multimodality: it emphasizes *presence*, the feeling to be in another world than the one we are in.
- When depicting Haptics, and more specifically in VR, an emphase should be added on whether it analyses *Haptic feedback*, *Haptic Interaction Techniques* or *Haptic Solutions*.

# 3

# VR Interactions via Haptic Solutions

Haptic Feedback, Haptic Interactions Techniques and Haptic Solutions in VR are distinct categories, yet they are intrinsically combined (Figure 3.1). Among these three categories, we depict two main actors: the User and the Designer. As [Kim and Schneider, 2020] mentioned it, tweaking *designers parameters* can drastically alter the *user experience*. While the User *performs* Interactions and *perceives* Feedback, the Designer *conceives* the Interaction techniques and *implements* their associated hardware solutions.

In these regards, we define the User experience as a combination of *Interaction Opportunities* - to which extent *users* can interact/act (e.g navigate, explore, manipulate) in a VR scene as opposed as in the real world - and the *Visuo-Haptic consistency* of the interaction, which refers to the tactile and kinesthetic feedback perceived during an interaction, using a given solution.

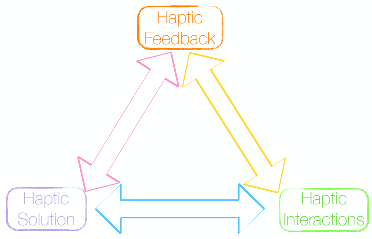



Figure 3.1: Reminder of the Three Haptic categories I distinguish.

Adopting an interface hardware perspective, we can translate UX-related questions into Designers parameters. The broadness of interactions and types of haptic features stimulated are defined in the interface's *modularity*. This also includes the types of scenarios the interfaces' enables ((non-) deterministic scenarios). The visuo-haptic consistency can be perceived as the interface's *degree of physicality*. This will later be depicted as whether the interface simulates an object or exploits one.

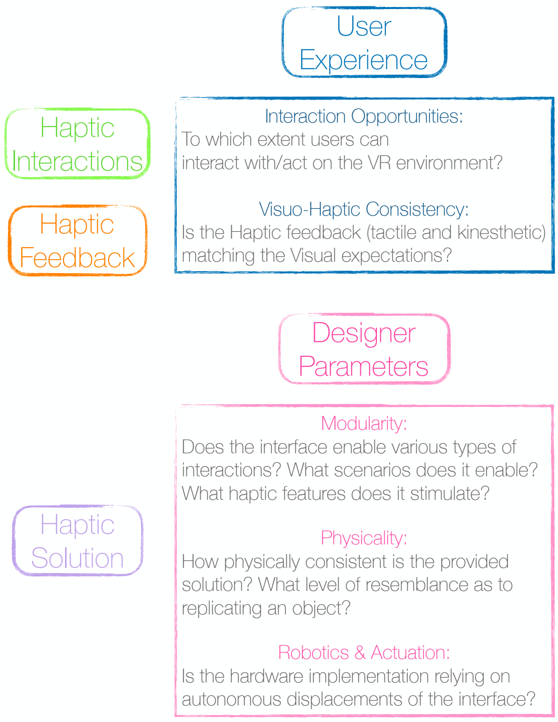



Figure 3.2: Criteria used in this chapter to define the User Experience. This chapter depicts Interactions via Haptic solutions: we will classify these solutions through Designer Parameters. Physicality and Robotics & Actuation are two orthogonal dimensions which will be depicted later on.

Another parameter is the interface's actuation: whether the interface relies on motor-based implementation, enabling autonomous displacements of the interface (eg changing its shape or position). This Robotics & Actuation *(degree of actuation)* parameter is later depicted as with/without robotics. It is orthogonal to the *degree of physicality*: this allows us to draw a 2D-design space to classify haptic solutions[1].

[1] *Modularity* is analysed depending on the design space category.

In this chapter, I first detail the available Haptic Interactions in VR, through their definitions, the available techniques and the challenges they face. Second, I depict Haptic Solutions through the physical consistency of their Haptic feedback, compared to the visual expectations; I create a continuum to identify their degree of physicality. Third, I focus on Haptic Solutions, through their hardware implementations. Finally, I compare three interfaces according to their interaction opportunities, physicality, modularity and actuation.

## *3.1 Analysis of VR Interaction Opportunities and Techniques*

In the real world, users **move freely** without constraints, **pick any object of their environment** and then **interact with their bare-hands**. They also can **be inter-**

**acted with**, from the environment (wind, unexpected obstacles) or from other users, for instance to catch their attention or to lead them somewhere. A natural environment also naturally physically constrains users through their **entire body**.

In this section, we build upon these real world tasks to discuss the interaction opportunities in VR and the current interaction techniques available to provide them. Interaction techniques is used in the HCI sense and are "the methods used to accomplish a given task via an interface" [LaViola et al., 2017]. Here, they are thus defined in a broader sense than the one often used in VR (referring to 3D interactions) [Bowman et al., 2001] as they include haptic rendering and feedback. More specifically, we discuss them through four main tasks: navigation, exploration, manipulation and edition. These are related to the interaction tasks in [LaViola et al., 2017], in particular, they have in common navigation and manipulation. However, we also include exploration and edition. An exploration task can only be defined with haptic feedback, it is probably why it is not present in [LaViola et al., 2017]. The edition task is considered in [LaViola et al., 2017] to be a part of the manipulation (modification of an object scale), yet we choose to dissociate it as it involves a different haptic rendering.

### *3.1.1 Navigation*

#### *Definition*

We qualify a navigation task as the exploration of the environment through the vision and the users ability to navigate through it via displacements. A navigation task can be perceived as a "non-haptic" task, however in VR, there are three main techniques to navigate in VR (described below), which all involve haptics. The two firsts rely on controllers and push buttons, where the users do not necessary physically move. The last one is more natural as it allows the users to walk in the VR arena (hence involves kinesthetic cues and more importantly, proprioception).

#### *Techniques*

*Panning* Panning is a common interaction technique from 2D graphics interfaces: it consists of moving a cursor over a 2D plane, which is augmented with *depth* - and hence 3D displacements - when users push a button to clutch their interfaces. This hence allows users to navigate within the environment and to change their points of view. This technique usually grounds the users mobility-wise, as it requires an interface (such as the Falcon, Figure 3.3) to be continuously held.

Figure 3.3: Novint Falcon grounded haptic interface

*Point & Teleport* With ungrounded solutions, such as controllers, the common technique is "teleportation". Users point their controllers [Baloup et al., 2018] to predetermined teleportation target areas, and are displaced into the selected area. This shows great advantages as it enables to navigate through the virtual environments even when the physical space is limited.

*Real Walking* Real walking in VR, *"perambulation"*, has shown the best immersion and presence results [Usoh et al., 1999, Steinicke et al., 2013]: it relies on proprioception and kinesthetic feedback through the legs and gait awareness. We can depict two methods for enabling real walk in a large workspace: (1) either the VR arena is room-scaled [Yixian et al., 2020], *or* (2) designers employ techniques to make users believe in an infinite workspace (Figure 3.4). This can be achieved through (a) an alteration of graphics rendering [Razzaque et al., 2001, Yang et al., 2019], (b) the use of robotised interfaces encountering the users feet [Iwata, 2005], (c) treadmills [Frissen et al., 2013, Vonach et al., 2017] or electrodes stimulating the users' muscles to move towards a chosen direction [Auda et al., 2019].

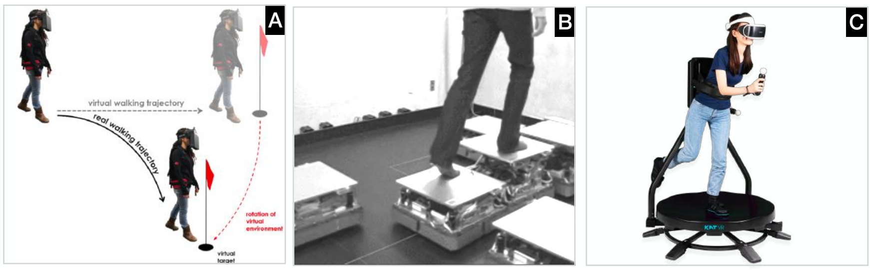



Figure 3.4: Real walking designers techniques when the workspace is not infinite: (A) Redirected walking, (B) Robotic platforms encountering the users' feet, (C) treadmills.

### *Challenges*

The challenges in a navigation task are within the users proprioception: panning or teleportation provoke a brutal transition from one place to another, which may cause some discomfort. Besides, users are not often provided with full body avatars, and hence lack their lower body parts (legs, feet). This lack of embodiment can result in some discomfort when using a *real walking* technique.

## *3.1.2 Exploration*

### *Definition*

As opposed to the previous definition of "navigation", based on vision cues, an "exploration" task consists in the ability to touch the environment and understand its constraints. Exploring thoroughly an environment in VR can be done through different haptic features, and can improve the users depth perception [Makin et al., 2019] or distances to an object. The different techniques for exploring the environment are detailed in Section 3.2.1.
Whenever a user is exploring the environment, shapes or textures are felt through his body displacements. He needs to move for his skin to stretch (through tactile cues) or his muscles to contract (through kinesthetic cues).

### *Techniques*

*God-Object* This technique is used when an interface is held within the users' hands. It is considered as a continuity of the users' hands, represented by a proxy that does not undergo physics or rigid collisions, and is attached to a complementary rigid object with a spring-damper model. This latter hence moves along with the proxy, but is constrained by the environment. Whenever it does collide with an object of interest, the users perceive the previous spring-damper stiffness through kinesthetic feedback. With the god-object principle, users can explore the environments' constraints through force-feedback. In this configuration, the users' arms are constrained by haptic desktop interfaces, providing strong enough forces to simulate a physical collision and discriminate shapes. Users hence interact through a proxy, like a desktop mouse, which position is not co-located with the users' vision. In healthcare and surgery training, users are more likely to interact with a tool, such as a scalpel or a clamp - continuously holding the god-object is hence not a constrain, however the co-location of vision and haptics is recommended [Ortega and Coquillart, 2005].

*Real Touch* In other scenarios, such as gaming, industry or tool training [Winther et al., 2020, Strandholt et al., 2020], using the appropriate tools through props and real objects is more natural. The users however need to be able to reach them whenever required. Whenever real props or material patches are available, users can naturally interact with their fingertips to feel different materials [Degraen et al., 2019, Mercado et al., 2021] (Figure 3.5 - A), shapes and patterns through their bare-hands [Cheng et al., 2017] (Figure 3.5 - B), textures [Benko et al., 2016, Lo et al., 2018] (Figure 3.5 - C) or temperatures [Ziat et al., 2014].

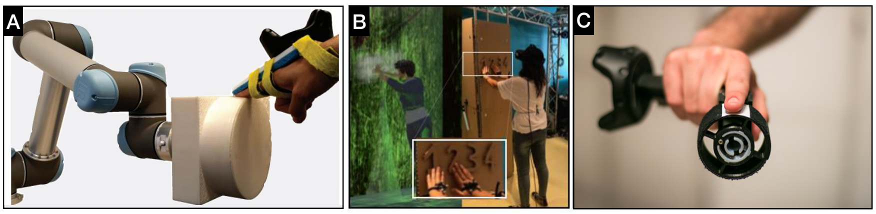



Figure 3.5: Exploration task: (A) Feeling materials [Mercado et al., 2021]; (B) Feeling patterns [Bouzbib et al., 2020]; (C) Feeling textures [Whitmire et al., 2018].

### *Challenges*

The challenges in an Exploration task is to be able to provide both tactile and kinesthetic feedback simultaneously. For instance, interfaces usually enabling large force-feedback (such as the Falcon seen in Figure 3.3) do not allow to discriminate intrisic features of an object (textures, materials), whereas real touch shows a variety of haptic feedback but cannot provide an adequate force-feedback/perceived stiffness. A good alternative is through the use of real objects: they benefit from their inherent properties and usually provide the correct amount of kinesthetic feedback.

### *3.1.3 Manipulation*

#### *Definition*

A manipulation task is performed whenever modifying the position and orientation of an object. In VR, we distinguish the *direct manipulation* [Bryson, 2005], *"the ability for a user to control objects in a virtual environment in a direct and natural way, much as objects are manipulated in the real world"* from virtually accessing an object, by pointing/selecting it with a controller.

#### *Techniques*

*Point & Select* Many manipulation techniques (selecting objects) have been developed in VR, either by having the users interact from outside the environment (World-In-Miniature, Scaled-World) or by embedding them into the environment (Go-Go, Simple Virtual Hand, Homer, Raycasting, Pointing) [Poupyrev et al., 1998, Poupyrev and Ichikawa, 1999]. This has the advantage of making all of the objects available for manipulation through controllers. Yet, haptic feedback-wise, only a slight vibrotactile feedback is usually perceived from the controller when an object is selected.

*Direct Manipulation* A direct manipulation relies on the ability to hold an object with kinesthetic feedback, "much as objects are manipulated in the real world" (Figure 3.6 - A): feel its weight [Lopes et al., 2017, Zenner and Krüger, 2019, Heo et al., 2018, Sagheb et al., 2019, Zenner and Kruger, 2017, Shigeyama et al., 2019] and constrains from the virtual environment, for instance when making objects interact with each other. Changing a virtual object position or orientation can be used as an input in the virtual environment: in [Zhao et al., 2017] for instance, the user modifies a light intensity by moving a handle prop in the real environment. By transposing [Lopes et al., 2015] in VR, an object could even communicate its dynamic use to the user (Figure 3.6 - B).

*Pseudo Manipulation* Leveraging vision over haptics allows to move an object with different friction, weights (Figure 3.6 - C) or force perceptions [Rietzler et al., 2018, Samad et al., 2019, Pusch and Lécuyer, 2011, Rietzler et al., 2019]. For instance, visually reducing the speed of a virtual prop displacement leads to an increase in the users' forces to move it, modifying their friction/weight perceptions, and consequently the perceived haptic feedback.

### *Challenges*

Manipulating an object through a controller is easy to implement and enables the user to choose any virtual object. Using real objects can provide more accurate information on the objects properties (eg weight) and constrains from the environment, yet this requires a thorough mapping between the physical/virtual artefacts. Technically-speaking, the props hence require to be accurately tracked within the environment. If markers are on top of a physical prop, it cannot be manipulated by its top: this is a current challenge in direct manipulation techniques.

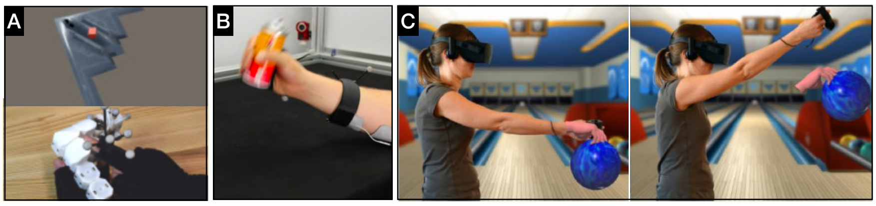



Figure 3.6: Manipulation techniques: (A) Direct manipulation of a prop [Zhao et al., 2017]; (B) Tranposing [Lopes et al., 2015] in VR, a prop could communicate its dynamic use; (C) Pseudo-haptic weight perception [Rietzler et al., 2018].

## *3.1.4 Edition*

### *Definition*

We qualify an Edition task as a modification of an object property, other than its orientation or position (for example through its scale [Xia et al., 2018] or shape).

### *Techniques*

*Physical Edition* Physically editing an object in VR requires an interface with movable parts, users could potentially physically modify. Editing an interface in VR would require it to be fully equipped with sensors: it needs to know its own position and configuration. For instance, modular interfaces can be rearranged to provide stretching or bending tasks [Feick et al., 2020], or be pushed on with a tool to reduce in size [Teng et al., 2019]. This "Physical Edition" technique could be leveraged by Shape-changing interfaces, dynamically modifying material properties [Nakagaki et al., 2016] or augmenting the interactions in Augmented Reality (AR) [Leithinger et al., 2013]. Yet, these only consider HMDs and VR as future work directions (Figure 3.7 - B). They are however relevant as 2.5D tabletops are already used in VR. Physically editing the virtual world through them could be implemented in a near future, by intertwining these interfaces with 3D modelling techniques [De Araújo et al., 2013].

*Pseudo Edition* This technique enables to visually change the object properties such as their shape [Achibet et al., 2017] (Figure 3.7 - A), compliance [Lee et al., 2019, Sinclair et al., 2019], stiffness [Villa Salazar et al., 2020] (Figure 3.7 - C), or their bending curvature [Heo et al., 2019] without having to physically edit the object. Pseudo-techniques are especially relevant for edition tasks: the user believes in an object's properties modification, but no physical modification nor tracking is occurring nor required.

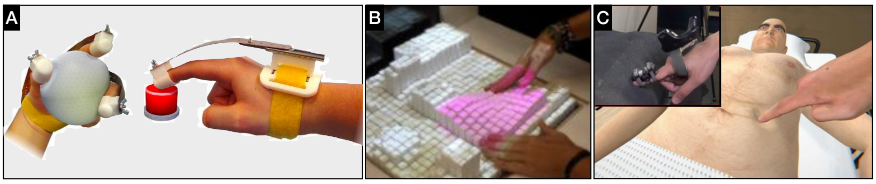



Figure 3.7: Edition task: (A) Changing a virtual object shape [Achibet et al., 2017] through the use of a wearable and pseudo-edition: the user virtually modifies the objects configurations - these changes are perceived through a stiffness change in the wearable interface. (B) Physically editing a shape changing device [Nakagaki et al., 2016] (not available in VR yet). (C) Perceiving compliance and stiffness changes using a wearable device and pseudo-edition [Villa Salazar et al., 2020]: the belly configuration is changing accordingly with the users displacements.

### *Challenges*

The difficulty behind the physical edition is how to render it in the virtual world. Recording a real-time change in a real object property requires it to be fully equipped with sensors. For editing tasks, an appropriate solution would be using a God-object: the stiffness perceived from the interface could actually match the modified object's compliance for instance. Using a pseudo-technique, the challenge relies in the believability of the edition, for instance the user could perceive that no physical change is occurring.

## *3.1.5 Environment-Initiated Interactions*

### *Definition*

In real environments with tangible interfaces, users usually are the decision makers and get to choose their points of contact during the next interaction. However, users themselves can be considered as tangible interfaces: uncontrolled interactions, such as being touched by a colleague, or feeling a temperature change in the environment [Shaw et al., 2019, Ziat et al., 2014], are part of everyday interactions that can be transposed in Virtual Reality.

### *Techniques*

As the user does not initiate the interactions, only "direct" techniques can be considered in this category (eg no pseudo-technique or tricks on the users perception can be used). These environment-based interactions involve multiple force types - tension, traction, reaction, resistance, impact - that help enhancing the user experience in VR

[Wang et al., 2020]. They have various effects on the user. For instance, replicating a social touch interaction in VR increases presence [Hoppe et al., 2020] and invokes emotions [Teyssier et al., 2020].
This type of interactions are recurrent in sports simulations, where the user is undergoing forces from his environment and perceiving impacts (jumping into space [Gugenheimer et al., 2016], shooting a soccer ball [Wang et al., 2020], goalkeeping in a soccer game [Tsai and Chen, 2019], paragliding [Ye et al., 2019], intercepting a volleyball [Günther et al., 2020], flying [Cheng et al., 2014]).

Figure 3.8: A robot initiates the interaction with the user, making him feel emotions [Teyssier et al., 2020].

*Challenges*

The challenge in enabling "environment-initiated interactions" mainly relies in the users behaviours: the user does not control the environment but is expected to have a certain behaviour. He also cannot decide to stop the interaction. When large forces are involved, an ethical issue can also be raised regarding the user safety.

### *3.1.6 Whole-Body Involvement*

*Definition*

All the previous subsections evoke interactions that mainly involve the hands or the fingers. Yet, we interact with our whole-body in the real life, and this should be transposed in VR. Moreover, VR applications usually force the user to maintain the same posture all along: this paradigm is revoked in "Either Give Me a Reason to Stand or an Opportunity to Sit in VR" [Zielasko and Riecke, 2020] - a user should be able to choose his posture.

Figure 3.9: Postures from [Teng et al., 2019].

*Technique*

This is currently only enabled in room-scale VR applications, where users experience sitting, standing, climbing [Teng et al., 2019, Suzuki et al., 2020, Danieau et al., 2012] and interact with their whole-body.

*Challenges*

In-between the *Navigation* and *Environment-initiated interactions* challenges, this whole-body involvement challenges remain in the tracking of the users' full body, and the usual lack of body avatar that causes a discomfort in the users' proprioception. For instance, prior to sitting, a user might want to be able to perceive his body avatar and ensure its position within the sitting area.

This section summarized the different User Interaction Opportunities and their associated techniques in VR. I believe that the variety of Interactions opportunities a Haptic solution offers is an important criterion to consider in its evaluation. This will be discussed in Section 3.4.

## 3.2 *Classification of Haptic Solutions in VR*

After enumerating the various tasks users can perform in VR, I discuss the Visuo-Haptic consistency (our second aspect of the user experience) of Haptic solutions from a Designer perspective: I define the interfaces' *degree of physicality* (Figure 3.10). This is the first dimension of the 2D-design space I propose to classify haptic solutions in VR (see Table 3.1).

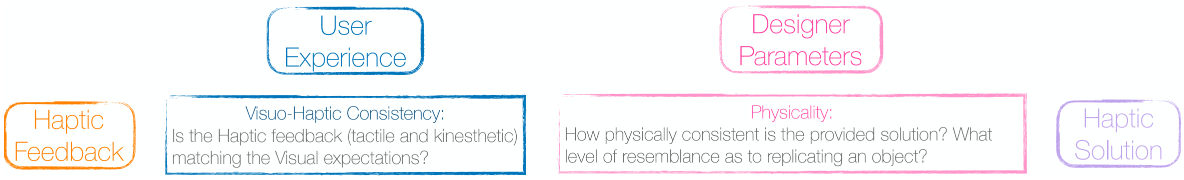



Figure 3.10: Parallel between User Visuo-Haptic consistency and Designers interfaces' degree of physicality.

The second orthogonal dimension I draw is their *degree of actuation*, ie whether haptic solutions rely on a motor-based hardware implementation enabling autonomous displacements (eg enabling to change its shape, position etc).

Table 3.1: I propose two dimensions to classify current solutions: their degrees of physicality and actuation.

| Physicality: Real Objects / Actuation: Robotics & Actuation | No | Yes |
|---|---|---|
| No | Shape Simulation<br>Pseudo-Haptics<br>Visuo-Haptic Illusions<br>Object Primitives<br>Surface Haptic Displays | Desktop Haptic Interfaces<br>2.5D Tabletops<br>Shape-Changing<br>Roboxels<br>Controllers<br>Wearables<br>Electro-Muscle Stimulation<br>Mid-Air Haptics<br>Inflatable Room Floor |
| Yes | Passive Haptics<br>Visuo-Haptic Illusions<br>Pseudo-Haptics<br>Human Actuators<br>Real Props Reassignment | Robotic Shape Displays<br>• Cartesian Robot<br>• Robotic Arm<br>• Swarm Robots<br>• Mobile Platforms<br>• Drones<br>• Merry-Go-Round Platform |

### 3.2.1 Physicality (designer), Visuo-Haptic Consistency (user)

The interfaces' *degree of physicality* corresponds to how the haptic perception is physically consistent/resembling with the virtual objects. This dimension is drawn as a continuum, from "no physicality" to "real objects" (see Figure 3.11). Yet, this continuum can be discretised as a two-category section: whether they use real objects or not.

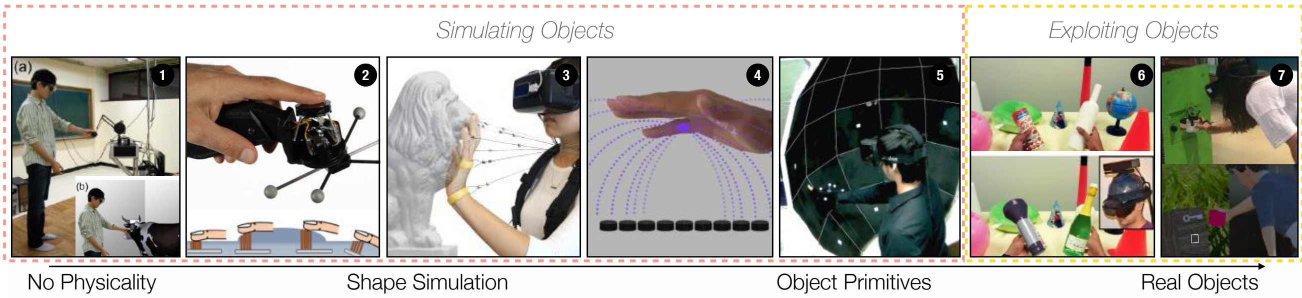



Figure 3.11: Degree of physicality continuum in VR. (1) Haptic desktop devices enable to explore the environment through a handle [Lee et al., 2009] with the god-object principle; (2) A controller [Benko et al., 2016] or (3) a wearable [Fang et al., 2020] simulate objects for exploration tasks; (4) Mid-air technology [Rakkolainen et al., 2020] create vibrations through the user's hand to simulate an object; (5) Passive proxies are oriented for the user to feel objects' primitives with their hands [Cheng et al., 2017]; (6) Objects from the environment are assigned to virtual props with the same primitives [Hettiarachchi and Wigdor, 2016]; (7) Real objects or passive props can be manipulated and interacted with each other [Bouzbib et al., 2020].

#### Simulating Objects

*No Physicality, (Figure 3.11 - 1)* Currently, grounded haptic devices such as the Virtuose [Haption, 2019] or the PHaNToM [Massie and Salisbury, 1994] simulate objects through their shapes (Figure 3.11 - 1). The rendering is only done through kinesthetic feedback via a proxy. Conceptually, the ideal link between the users and this proxy is a massless, infinitely rigid stick, which would be an equivalent to moving the proxy directly [Hayward and Maclean, 2007, Sato, 2002]. These solutions only provide stimulation at the hand-scale, with no regards to the rest of the body.

*Shape Simulation, (Figure 3.11 - 2-3-4)* In the same regards, gloves or controllers provide some physicality (Figure 3.11 - 2-3). Gloves or exoskeletons for instance provide physicality through kinesthetic feedback. They can constrain the users' hands by *blocking* them into positions [Gu et al., 2016, Fang et al., 2020], but cannot resist with too much force over the users' hands and usually cannot provide any feedback through the users' palm. These can be extended to overall body suits for users to feel impacts or even temperature changes [VRElectronicsLtd, 2019, Danieau et al., 2018], or even intertwined with grounded devices to extend their use-cases [Steed et al., 2020].
Customised controllers are currently designed to be either stimulating the palm [Sun et al., 2019, Yoshida et al., 2020, de Tinguy et al., 2020] (Figure 3.13 - 1, 2), or

held in the palm while providing haptic feedback on the fingertips. For instance, [Whitmire et al., 2018] proposes interchangeable haptic wheels with different textures or shapes, while [Benko et al., 2016] enables textures and shapes and [Lee et al., 2019] displays compliance changes. In these configurations, users hold a single controller, however bi-manual interactions can be created by combining two controllers. Their link transmits kinesthetic feedback, and constrain their respective positions to each other [Strasnick et al., 2018, Wei et al., 2020].

Shape simulation can also be achieved through unencumbered technologies, as per Krueger's postulate [Wexelblat, 1993] (see Introduction). While studies demonstrated that interacting with bare-hands increased the user's cognitive load [Galais et al., 2019], combining bare-hands interactions with haptic feedback actually enhances the users involvement. For instance, contactless technology (Figure 3.11 - 4) has also been developed for simulating shapes: it sends ultrasounds to the users hands, for them to perceive shapes on their skin, without a physical prop contact [Rakkolainen et al., 2020, Carter et al., 2013].

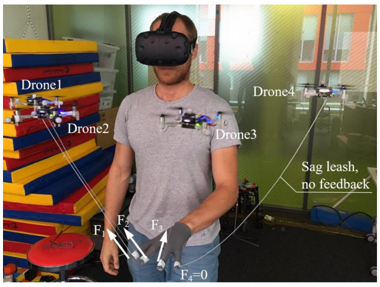



Figure 3.12: Swarm of Drones for Interactions [Tsykunov and Tsetserukou, 2019].

These unencumbered methods are also achieved through shape-changing interfaces, for instance with balloons arrays [Takizawa et al., 2017] or 2.5D tabletops (Figure 3.13 - 3, Figure 3.6 - 5) [Follmer et al., 2013, Siu et al., 2018, Iwata et al., 2001]. These latter are constituted from pins, that raise and lower themselves to replicate different shapes. In the same regards, swarm interfaces rearrange themselves to display different shapes. These have mainly been developed in the real world [Le Goc et al., 2016, Suzuki et al., 2018, 2019] but slowly take off as VR user interfaces [Zhao et al., 2017] (Figure 3.6 - 4). Indeed, while these latter devices are used as desktop interfaces, the swarm robot idea has extended to the air, with the recent use of small drones [Tsykunov and Tsetserukou, 2019] (see Figure 3.12).

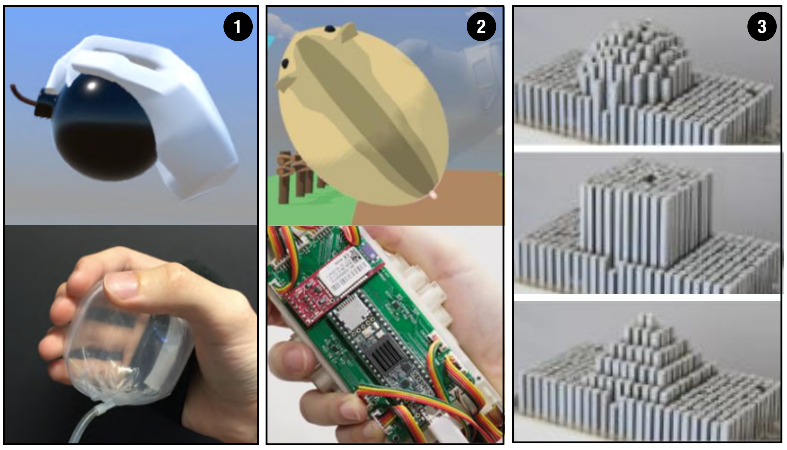



Figure 3.13: Simulating Objects. (1) A controller with an inflatable prop in the user's palm simulates holding a bomb [Teng et al., 2018]. (2) A pin-based interface shaped as a ball interacts in the user palm to replicate a hamster [Yoshida et al., 2020]. (3) Different primitives (ball, cube, pyramid) are displayed on a 2.5D tabletop [Siu et al., 2018].

*Object Primitives, (Figure 3.11 - 5)* Finally, a user can interact with object primitives. These represent the simplest geometries available: circle, cube, pyramid, cylinder, torus. Simply feeling an orientation through the fingertips provides the required information to understand an object shape, in an exploration task for instance. Panels with diverse orientations can hence be displayed for a user to explore various objects in a virtual environment [Cheng et al., 2017] (Figure 3.11 - 5) or directly encounter the user at their position of interest [Yokokohji et al., 2005, 2001].

On the opposite, a bare-hands manipulation requires multiple primitives to be available simultaneously within the hand vicinity. This is why the exploitation of real objects is necessary.

### *Exploiting Real Objects*

Passive haptics [Insko, 2001], ie the use of passive props and tangible objects, consist in placing real objects corresponding to their exact virtual match at their virtual position. Insko demonstrated that passive haptics enhanced the virtual environment [Insko, 2001]. Nonetheless, this does suffer from a main limitation: substituting the physical environment for a virtual one [Simeone et al., 2015] requires a thorough mapping of objects shapes, sizes, textures, and requires numerous props. This can be done with real objects in simulation rooms for instance (e.g plane cockpit, motorcycle), but cheaper methods need to be implemented to facilitate their use in other fields.

*Objects with Similar Primitives, (Figure 3.11 - 6)* One solution is to extract the primitives of the objects that are already available in the physical environment, to map virtual objects of the approximate same primitive over them [Hettiarachchi and Wigdor, 2016] (Figure 3.11 - 6). In order to multiply the number of available props in the environments, two main techniques can be drawn:

- *Visuo-Proprioceptive Illusions & Pseudo Haptics.* The number of props within the environment can be reduced, while letting the users interact at different positions of the physical world. It is possible to leverage the vision over haptics and modify the users' proprioception to redirect their trajectory [Kohli, 2010, Kohli et al., 2012, 2013, Azmandian et al., 2016, Gonzalez and Follmer, 2019, Han et al., 2018]. A user might perceive multiple distinct cubes for instance, while interacting with a single one. On the same principle, the user hand displacement can be redirected at an angle, up-/down-scaled [Abtahi and Follmer, 2018, Bergström et al., 2019], or slowed down for friction or weight perception [Samad et al., 2019, Praveena et al., 2020]. These techniques also allow for the exploration and manipulation of various shapes: models can for instance be added to enable complex virtual shapes to be mapped over real physical objects boundaries [Zhao and Follmer, 2018]. A user can also pinch different geometries without perceiving any discrepancy, as long as the spacing is consistent [de Tinguy et al., 2019]. This was tested using a multi-primitive physical totem (Figure 3.14). This can be used in redirection techniques to an extent where this single totem could represent various objects from the virtual scene. This would hence reduce the number of objects available in the physical scene.

On the same principle, pseudo-haptics allow to modify the users' shape [Ban et al., 2012,] or texture [Degraen et al., 2019] perceptions when interacting with a physical prop.

Figure 3.14: A Multi-primitive totem (Cylinder, Pyramid, Cube) [de Tinguy et al., 2019].

- *Displacing Objects, (Figure 3.11 - 7).* Whenever objects are indeed available within the environment, various approaches are available to displace them. This displacement allows for mapping one physical object over multiple ones, but also to display a multitude of props. These directions embrace the *Robotic Shape Display* principle from *Robotic Graphics* [McNeely, 1993]: "a robot that can reach any location of a virtual desktop with an end-effector" and matches the user's object of interest.
  Their usability have been validated through a Wizard-of-Oz implementation, where human operators move real objects or even people around a Room-scale VR arena to encounter the users [Cheng et al., 2015] (Figure 3.17 - 2). The users themselves can also reconfigure and actuate real props [Cheng et al., 2018].
  Robotic Shape Displays, RSDs, are also called **encountered-type of haptic devices**, as they literally encounter the users at their object of interest to provide haptic feedback. They allow to display real pieces of material [Araujo et al., 2016, Abtahi et al., 2019], physical props to simulate walls [Kim et al., 2018, Yamaguchi et al., 2016], or even display furniture [Suzuki et al., 2020] or untethered objects [He et al., 2017,, Huang et al., 2020], that can be interacted with each other.

*Real Objects, (Figure 3.11 - 7)* Finally, every object from the real environment can be paired with a virtual counterpart. This is instantiated in *Substitutional Reality* [Simeone et al., 2015] or most commonly in Simulation rooms.

> This section classified Haptic solutions through their degree of physicality. From a User experience perspective, this can be perceived as the Visuo-Haptic Consistency an interface provides. We should consider taking this degree of physicality when evaluating a Haptic Solution.
> Besides, we observed that the physicality continuum can be depicted in two cate-

gories: whether it simulates an object or exploits one. Theoretically, exploiting passive props should increase the user experience, compared to simulating them.

### 3.2.2 *Robotics and Actuation*

The previously evoked haptic solutions were classified whether they used real objects or not. In this section, we finally depict the different haptic solutions from a Hardware perspective, whether they rely on Robotics and Actuation or not.

This hence provides us with four categories, in which Haptic solutions are classified into. We will describe them through their operational and implementation costs (eg operator required, tracking etc), and through their modularity, defined as:

- Haptic Feedback variety: this corresponds to the types of haptic features that are stimulated whilst using the given interface;
- Interactions variety: this corresponds to the broadness of interactions enabled by the interface;
- Use-cases variety: this corresponds to the broadness of use-cases an interface enables, and its associated deployment opportunities;
- Scenario types: we distinguish here scenario-based experiences from *non-deterministic scenarios*, where the user can interact with *any* object with no regards to the scenario's progress.

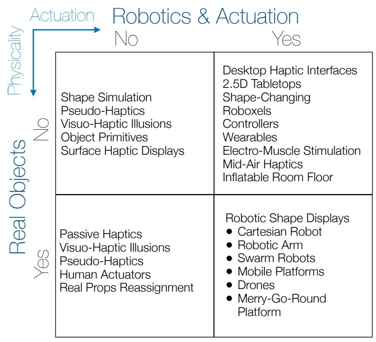



Figure 3.15: Reminder of our Design Space.

For instance, using a classic controller does not provide a haptic or interaction modularity, yet it enables non-deterministic scenarios: a user can point towards and interact with literally any object within the scene. On the opposite, the use of real objects is for instance promising and enhances the user experience through various shapes, textures, sizes. It is though difficult to replicate the entire virtual environment and make it available for interacting in non-deterministic scenarios. Hardware-wise, this can be solved using a graphics-based method: redirection. Otherwise, a robotic interface could displace props around the VR arena.

Finally, we extract criteria such as safety, speed/accuracy, robustness and ease-of-use from [Dominjon et al., 2007] when depicting Robotised interfaces.

#### *No Robotics*

We depict here an important design choice when opting for these solutions: either the designer relies on **graphics solutions**, leveraging vision cues over haptic ones, or needs **operators** to displace or change the interactable props (see Table 3.1).

*Passive Haptics.* Passive Haptics [Insko, 2001] only consist in placing real objects corresponding to their exact virtual match at their virtual position. They provide a natural way of interacting through the objects' natural affordances [Norman, 2013]. They however are limited to the available objects within the scene as they are not actuated. They only can be used in a scenario-based experience, where the target is known in advance. The environment hence requires a physical prop to overlay each available virtual object.

*Pseudo-Haptics, Visuo-Haptic Illusions, Object Primitives.* For graphics solutions, users are redirected towards their object of interest [Azmandian et al., 2016] using visuo-haptic illusions. However, physically overlaying a prop or primitive over a virtual object has a tracking cost, which usually relies on trackers which can be operationally costly (eg Optitrack [Optitrack, 2019] or HTC Trackers).

Otherwise, the users intentions have to be predicted for the interaction to occur. The users hands are then redirected to the appropriate motionless prop, to explore the adequate object of interest [Cheng et al., 2017]. Operationally, the cost only relies on the proxy fabrication (Figure 3.11 - 5). These implementations offer various scenarios in terms of interaction (even non-deterministic), at an affordable cost.

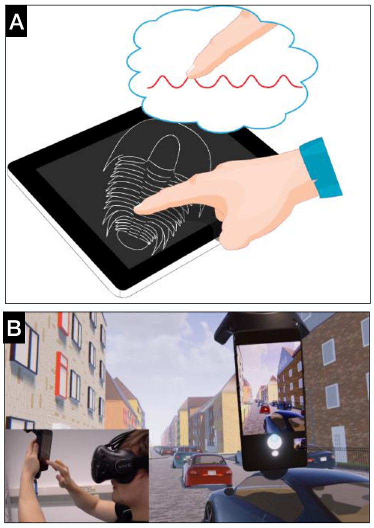



Figure 3.16: A. "Tactile bump-rendering algorithm would allow the user to experience rich tactile textures on flat touch screens." [Kim et al., 2013] B. A user interacting with a smartphone in VR [Savino, 2020].

*Surface Haptic Displays.* These techniques exclusively allow for exploration through multiple haptic features such as friction or textures [Kim et al., 2013] (Figure 3.16 - A). They also can integrate a tablet or a smartphone (Figure 3.16 - B) [Savino, 2020], on which the user can interact at any location.

*Human Actuators.* This technique consists in using human operators to displace props in the VR arena. The designers however come across reliability and speed issues with these operators. Even though they only are used in scenario-based experiences, *delay mechanisms* based on graphics need to be implemented [Cheng et al., 2015] (Figure 3.17 - 2) to overcome these issues. Conceptually, they broaden the interaction scope, however this solution is operationally very costly.

*Real Props Reassignment.* Instead of using a tracking system for passive props, a depth camera for instance allows to identify the props basic primitives and to reassign them to different virtual counterparts of the same primitive [Hettiarachchi and Wigdor, 2016] (Figure 3.11 - 6). The objects are hence all available to be interacted with. This drastically reduces the operational costs as they only rely on computer vision. This enables non-deterministic scenarios as the real world is literally substituted for a virtual one [Simeone et al., 2015] and objects can be reassigned with virtual:physical [He et al., 2017] mappings.

### *Robotics & No Real Objects*

This section gathers solutions simulating the virtual environment through actuation: they replicate it to constrain the users.

*Desktop Haptic Interfaces.* The SPIDAR [Sato, 2002], the Virtuose [Haption, 2019], the Falcon (Figure 3.3) and other classic desktop haptic interfaces are already compared in multiple surveys [Dominjon et al., 2007, Seifi et al., 2019, Wang et al., 2019] (see Figure 3.11 - 1). They are safe as they are controlled by the user and only constrain their arm movements with kinesthetic feedback and adapt to any available object from the virtual scene (non-deterministic scenarios). They show a high perceived stiffness and robustness, but remain really expensive (>10k$).

*Shape-Changing Interfaces, 2.5D Tabletops.* These solutions present a high perceived stiffness and change their shapes accordingly with the virtual environment [Fitzgerald and Ishii, 2018, Leithinger et al., 2013]. They hence do not require any operator and allow for non-deterministic scenarios whenever their displacements are enabled [Siu et al., 2018] (see Figure 3.13 - 3). They are however complex to build: they require multiple motors[2], which define their haptic fidelity resolution. Even though they present high voltages, they remain safe around the users. As they enable bare-hands interactions, they show a high ease of use.

[2] 2.5D tabletops are composed of arrays of numerous pins.

*Wearables, Controllers, EMS.* These rely on small torques, which are sufficient to constrain the users body parts (Figure 3.13 - 1,2). They are safe and easy to use, but in return are not robust enough to resist to users' actions. As they are continuously changing the users' haptic perception, they do allow non-deterministic scenarios and change their rendered stiffness and rigidity as a function of the distance to a virtual prop [de Tinguy et al., 2020, Kovacs et al., 2020]. A customised controller usually relies on 3D printed parts and small servomotors and can be easily replicated [Sun et al., 2019] (Figure 3.11 - 2,3).

*Mid-Air Haptics.* Providing contactless interactions (Figure 3.11 - 4), mid-air haptics also provide a high level of safety around the user. They however do not allow to navigate the VR environment, and hence cannot consider non-deterministic scenarios. Their robustness is very low, as they send ultrasounds to the users and do not physically constrain them [Carter et al., 2013].

*Inflatable Floor.* The floor topology can be modified and inflated to create interactions at the body-scale [Teng et al., 2019] (see Figure 3.9). The users cannot inflate them, however they can push some tiles down and hence, *edit* them. These are safe, though they do not provide a wide range of interactions, but offer multiple static body postures.

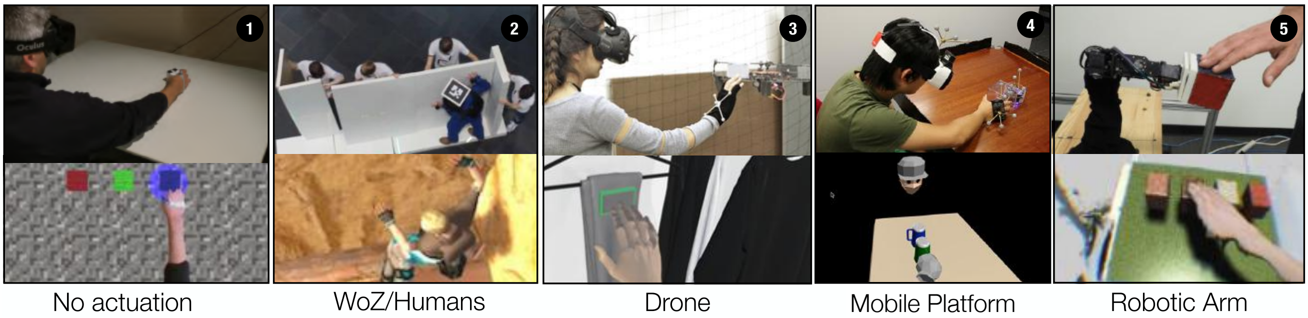



Figure 3.17: Degree of Actuation. (1) No actuation is available. The user's hand is redirected to touch a passive prop that cannot move [Azmandian et al., 2016]. The implementation of this technique relies exclusively on a software development leveraging the vision cues; (2) Human actuators are used to illustrate the Robotic Graphics [McNeely, 1993] principle with a Wizard of Oz technique [Cheng et al., 2015]. They carry props for the user to feel a real continuous wall; Encountered-type of haptic devices (3-5): (3) A drone encounters the users' hand for exploring passive props; (4) A mobile platform displaces itself for users to interact with physical props [He et al., 2017]; (5) A robotic arm with multiple degrees of freedom displaces itself to encounter the users' hand, and rotates its shape-approximation device to provide the right material [Araujo et al., 2016].

### *Robotics & Real Objects*

In this subsection, we detail the different types of Robotic Shape Displays - otherwise known as "**encountered-type of haptic devices**", mentioned in the Table 3.1. First, these interfaces move to encounter the users: this feature optimises their ease of use. Second, as these interfaces move within the user vicinity, safety concerns are raised in this section, depending on the interfaces robustness.

Encountered-type of haptic devices combine different types of interaction techniques: they can provide the users with passive props, textures or primitives, and allow navigation, exploration, manipulation tasks. Their mechanical implementations offer a good repeatability and reliability.

*Robotic Arm.* A robotic arm theoretically provides many degrees of freedom. This primarily means a higher cost and a higher safety risk. For instance, H-Wall, using a Kuka LBR Iiwa robot, presents high motor torques and can hence increase the safety risks around the users [Kim et al., 2018, Mercado et al., 2021]. This implementation hence does not allow non-deterministic scenarios, and presents either a wall or a revolving door to the user, with a high robustness. Implementations with smaller torques, such as [Vonach et al., 2017, Araujo et al., 2016] are safer but display a reduced perceived stiffness. The use-cases for all these interactions are hence drastically different: H-Wall simulates a rigid wall while VRRobot [Vonach et al., 2017] and Snake Charmer [Araujo et al., 2016] (Figure 3.17 - 5) present more interaction opportunities. This latter is also the single Robotic Shape Display that autonomously changes its end-effector, without an operator. A novel implementation was designed using wearable robotic arms [Horie et al., 2021]. They aim to let the user free to navigate and encounter him when an interaction is required; this solution is however quite encumbering.

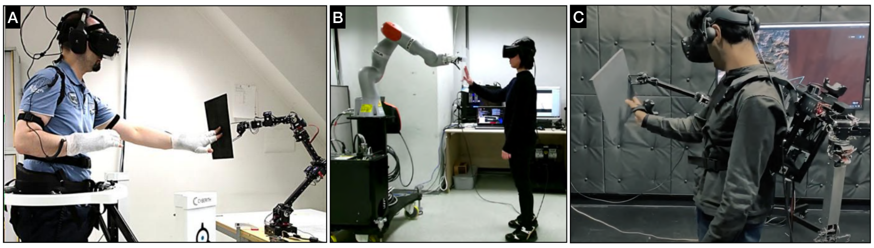



Figure 3.18: A. VRRobot [Vonach et al., 2017]; B. H-Wall [Kim et al., 2018]; C. Encountered-Limbs (wearable robotic arms) [Horie et al., 2021].

*Drones.* With drones (see Figure 3.17 - 3, Figure 3.19), the modularity in the interactions are quite limited, for instance [Yamaguchi et al., 2016] only enables to interact with a single wall at a given position, via a proxy object. Going from an active mode (flying) to a passive one (graspable by the user) has a long delay (10s) [Abtahi et al., 2019], which on top of the safety concerns, does not allow non-deterministic scenarios. [Tsykunov et al., 2019] however allows the user to change the drone trajectory to fetch and magnetically recover an object of interest. Their accuracy and speed are limited compared to the previous grounded interfaces, and can require dynamic redirection techniques to improve their performances. As they are ungrounded, they do not have a high robustness nor perceived stiffness. Their use-cases are quite limited at the moment, mostly due to the drone's noise and the wind the lack of transparency from its thrust.

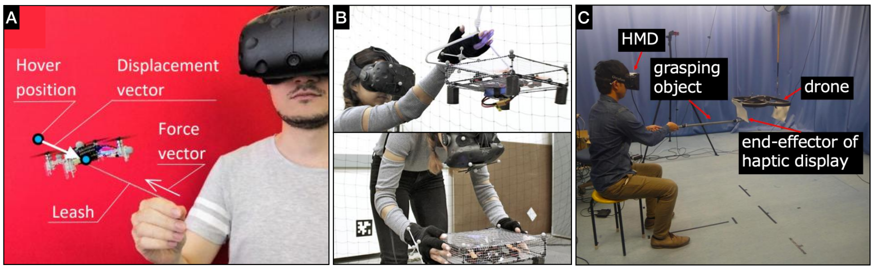



Figure 3.19: A. SlingDrones, magnetically recovering objects of interest [Tsykunov et al., 2019]; B. Beyond the Force drone, enabling only light passive props manipulation because of the drone's thrust [Abtahi et al., 2019]; C. Touching a drone through a proxy because of the drone's thrust [Yamaguchi et al., 2016].

*Mobile Platforms.* Similarly to the drones, the ungrounded aspect of the mobile platforms does not guarantee their robustness or perceived stiffness, and these do not show high speeds at the moment (max $0.3m/s$), which may be sufficient for desktop interactions (see Figure 3.17 - 4). They however display a good accuracy ($< 5mm$ [Gonzalez et al., 2020]). To decrease the conception cost, existing vacuuming robots are used as mobile platforms in [Wang et al., 2020, Yixian et al., 2020]. Designers can choose to duplicate them, as swarm robots, to enable non-deterministic scenarios

[Suzuki et al., 2020]. These are safe to use around the users, as their speed and robustness are limited. A merry-go-round platform can also be designed to display various props at an equidistant position from the user [Huang et al., 2020].

All of the previous interfaces require an operator cost on top of their mechanical and software ones, to modify the interactable props available, depending on the use-cases.

*Swarm Robots.* On the opposite, [Zhao et al., 2017] proposes autonomous reconfigurable interfaces intertwining both Robotic Shape Displays principle and "shape-changing" interfaces to get rid of the operator cost (see Figure 3.6 - 4). These small robotic volume elements reconfigure themselves into the users objects of interest. They have a sufficient perceived stiffness to represent objects, but are not robust enough to resist to body-scaled forces, for instance to simulate rigid walls.

> We classified Haptic solutions through two dimensions: whether they exploit real objects or not, and whether they use robotics and actuation or not.
> We described each Haptic solution through their modularity, which we defined as a combination of Haptic feedback, Interaction, Use-cases varieties, and the types of Scenarios enabled. Finally, we used additional criteria to qualify Robotised interfaces: their accuracy/speed, their safety, robustness and ease-of-use.

## 3.3 *Synthesis*

By understanding the parameters defining the User Experience (here Interactions opportunities and Visuo-Haptic consistency), we can find Designer parameters to cover these requirements.

In designing a Haptic Solution, many parameters need to be taken into account, such as the interface's robustness, its safety around users, its modularity (interactions, haptic feedback, types of scenarios), its ease-of-use, its tracking or operational costs.

Depending on the use-cases and haptic interactions the designers want to enable, various haptic solutions of different complexities can be implemented. The whole design process of a haptic solution is hence a compromise between implementation challenges and users experiences. This can be seen through the different use-cases enabled by a haptic solution: the more haptic solutions have technical difficulties (safety, speed, accuracy), the less deployment opportunities.

## 3.4 *Example: Comparing Encountered-Type of Haptic Devices*

We summarize here the criteria gathered throughout our Interaction Opportunities[3], Physicality and Robotics & Actuation sections, to compare three encountered-type of haptic devices: Beyond the Force (BTF) drone [Abtahi et al., 2019] (Figure 3.17 - 3), ShapeShift [Siu et al., 2018] (Figure 3.13 - 3), Snake Charmer [Araujo et al., 2016] (Figure 3.17 - 5).

[3] Navigation is described through the available workspace.

In terms of interactions and number of props, the drone is the most limited one. Indeed, because of both safety and implementation limitations, it only enables free navigation in a reduced workspace. It also allows exploration (through textures) and manipulation tasks. However, the manipulation task is at the moment limited to a single light object as BTF cannot handle large embedded masses yet. Whenever grabbed, it does not provide a haptic transparency [Hayward and Maclean, 2007] during the interactions because of its thrust and inertia. For the users to perform different tasks, an operator needs to manually change the drone configuration. Its mechanical implementation does not provide a sufficient speed for overlaying virtual props in non-deterministic scenarios, but its accuracy is also unsatisfactory and requires dynamic redirection techniques for the interactions to occur. It also provides unwanted noise and wind, which reduces the interaction place of illusion.

| | Interaction Opportunities | | | | | | Physicality | Modularity | | | | Actuation & Robotics | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Navigation Workspace | Haptic Features | Exploration | Manipulation | Edition | Whole-Body Involvement | Passive Haptics | Number of Props | Operator | Non-Deterministic Scenarios | Deployment Use-cases | Robustness | Accuracy Speed | Safety | Ease-of-Use |
| Beyond the Force | $2m^3$ | ++ | ++ | + | - | - | Yes | Prepared prior to use | Yes | - | / | - | - | - | +++ |
| ShapeShift | Desktop | + | +++ | + | + | - | No | ∞ | No | ++ | 3D Terrain Volumetric Data | ++ | + | +++ | +++ |
| Snake Charmer | Desktop | +++ | +++ | ++ | - | - | Yes | Prepared prior to use | No | ++ | Training | + | + | ++ | +++ |

Table 3.2: Comparison & Evaluation of three Encountered-type of Haptic Devices, according to Interaction, Modularity and Actuation parameters.

ShapeShift [Siu et al., 2018] is drastically different: it is a 2.5D desktop interface that displaces itself. Even though a drone is theoretically available in an infinite workspace, in practice they do share approximately the same one. As [Siu et al., 2018] relies on a shape-changing interface, no operator is required and it shape changes itself to overlay the users' virtual objects of interest, in non-deterministic scenarios. It allows a free navigation at a desktop scale, as well as bimanual manipulation and exploration. Both of these devices haptic transparency are limited as they are ungrounded solutions. We believe that ShapeShift could be updated to allow Edition tasks, by synchronising the users force actions with the actuated pins stiffness. In terms of haptic features, it simulates shapes and stimulates both tactile and kinesthetic cues. As per all 2.5D tabletops, it can be used in various applications: 3D terrain exploration, volumetric data etc. Its resolution seems promising as its studies shows successful object recognition and haptic search.

The same interactions are available at a desktop scale with Snake Charmer [Araujo et al., 2016], which provides a wide range of props and stimulation, as each of its end-effector include 6 faces with various interaction opportunities (textures to explore, buttons to push, heater and fan to perceive temperature, handle and lightbulb to grasp and manipulate...). It also can change its shape approximation device, SAD (ie its end-effector), autonomously, using magnets. It follows the user hand and orient the expected interaction face of its *SAD* prior to the interactions: it hence enables non-deterministic scenarios. Besides, Snake Charmer has a promising future regarding its deployment: *LobbyBot* [noa], is already in the Renault industry research lab, to enable VR haptic feedback in the automotive industry.

Room-scale VR becomes more and more relevant, and Snake Charmer could benefit from being attached to a room-scaled mobile platform (either on the ground or a drone). Similarly, intertwining mobile platforms with a robotic arm autonomously changing its SAD like Snake Charmer or with a shape-changing interface could reduce regular Robotic Shape Display operational costs. This would leverage all of the Robotics Graphics concept capabilities.

## *3.5 Conclusion*

We analysed haptic interactions in VR and their corresponding haptic solutions. We analysed them from the user perspective by considering interaction opportunities and visuo-haptic consistency. From a designer perspective, we proposed to classify haptic solutions through a two-dimension design space: the interfaces' degree of physicality and degree of actuation.

We first described haptic interactions techniques in VR. Implementation-wise, we analysed the interfaces robustness, their ease of use as well as their safety considerations. From an operation perspective, we also analysed the costs of the proposed solutions. We highlighted the variety of props, tasks and haptic features that a haptic solution can potentially provide in VR. This can be used to analytically evaluate the existing haptic solutions. It can also help VR designers to choose the desired haptic interaction technique and/or haptic solution depending on their needs (tasks, workspace, robustness, use-cases etc).

Combining multiple haptic solutions can benefit the user experience, as it optimises the above criteria. Encountered-type of haptic interfaces were highlighted as they already combine multiple interaction techniques: they displace passive props in potentially large VR arenas and allow for numerous tasks, such as navigation, exploration, manipulation, and even allow the user to be interacted with. An analysis of these interfaces will hence be depicted in the next chapter of this dissertation.

WHAT YOU MUST REMEMBER

*Positioning:*

- Designing a Haptic Solution differs depending on the Haptic Interaction opportunities a user can perform and the Haptic feedback being provided.

*Contributions:*

- The user experience can be depicted through (a) the variety of interactions opportunities and (b) the visuo-haptic consistency of the feedback.
- Haptic Solutions can be depicted through their (a) degree of physicality and (b) degree of actuation, and qualified through (c) their modularity.
- Encountered-type of Haptic solution show a promising potential for providing Haptics in VR.

# 4

# Robotic Graphics: a Failure Mode Analysis

In this chapter, we focus on *Robotic Graphics*, a principle conceived by McNeely in the 90s [McNeely, 1993]. These are also referred to as *Encountered-type of Haptic Displays - ETHD*, or *WYSIWYF*[1] *displays*. From all these names, we understand that these interfaces encounter the users at their object of interest with an appropriate visuo-haptic consistency. The previous chapter showed the promising future of these interfaces for enhancing Haptics in Virtual reality experiences. This chapter provides an analysis of these interfaces, principally through their failure modes and the associated solutions for mitigating them. This "Failure mode" approach is a common protocol in Industries and Quality Control [Stamatis, 2003], and I believe that using this method can provide the necessary step back to improve the ETHD usability and facilitate their deployment, through the understanding of the ETHD designing challenges. Instead of focusing on physicality, modularity or actuation parameters such as in Chapter 3, I focus here on the principal functions ETHDs *must* cover, in order to refine their global specifications.

[1] What You See Is What You Feel

Encountered-type of Haptic Displays enable Unencumbered Haptic Interactions in VR. They hence represent a large portion of the Haptic Solution category from

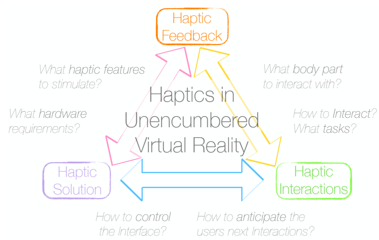



Figure 4.1: Reminder of our three categories and their associated research questions.

our triangular approach (Figure 4.1), centered around Haptics in Unencumbered VR. This chapter provides a groundwork to answer our HAPTIC SOLUTION-related research question (Chapter 1):

*What requirements for an interface enabling unencumbered haptic interactions in VR?*

This chapter analyses the challenges in the design and implementation of an ETHD interface, their effects on the user experience, and the solutions alleviating them:

– At a *Haptic Solution* and *Haptic Feedback* intersection, I analyse how the designer conception phase impacts the user perception one: failures in the perception phase result from failures in the conception phase.

– At a *Haptic Solution* and *Haptic Interactions* intersection, I depict the classic *Robotic Graphics* scenario: I analyse how the users eventually interact with an interface that encounters them at a location of interest. I describe the potential failures from this scenario.

– At a *Haptic Interactions* and *Haptic Feedback* intersection, I analyse the failure modes from a *perception* perspective, ie when the visual and haptic feedback are not consistent.

## 4.1 Robotic Graphics

### 4.1.1 Definitions

In this section, I summarize the various names and definitions referring to Robotic Graphics. McNeely's Robotic Graphics are split into two distinct categories: **Robotic Shape Displays** and **Roboxels** [McNeely, 1993].

*Robotic Shape Displays - RSD* "A robot is present that can **reach** any location on the virtual desktop with an end effector [...] When the system **anticipates** contact, it orders the robot" for the interaction to occur.

*Roboxels* "cellular robots that dynamically configure themselves into the **desired shape and size**, lock together and simulate the **desired object**[2]." They can be used for exploration or manipulation tasks. They can also be synchronised with the users gestures to enable edition tasks (see Section 3.1 in previous chapter).

[2] Roboxel is standing for "robotic volume element.

The keywords in McNeely definitions are displayed in bold: these interfaces *capture* the users intentions and exploit them to define their intended object of interest ("desired shape, size, object") to **anticipate** contact and *display/simulate* the adequate object of interest at the users **desired** location.

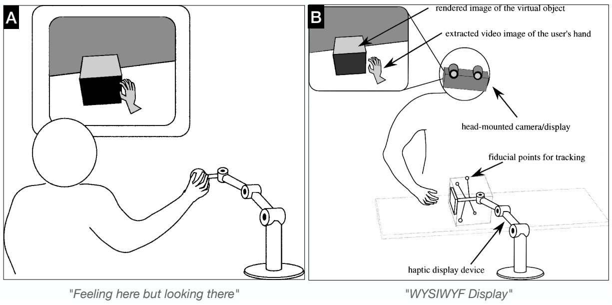



Figure 4.2: Illustrations from [Yokokohji et al., 1996]: (A) Feeling here but seeing there; (B) WYSIWYF Display.

*WYSIWYF displays* "The proposed concept provides correct visual/haptic registration using a vision-based object tracking technique and a video keying technique so that what the user can see via a visual interface is consistent with what he/she can feel through a haptic interface. The user's hand "encounters" the haptic device exactly when his/her hand touches a virtual object in the scene" (Figure 4.2) [Yokokohji et al., 1999].

*Encountered-type of Haptic displays - ETHD* "Encountered-type haptic displays recreate realistic haptic sensations by producing physical surfaces on demand for a user to explore directly with his or her bare hands" [Yamaguchi et al., 2016, Gonzalez, 2015]. "Encountered-Type Haptic Displays provide haptic feedback by positioning a tangible surface for the user to encounter" and "can generate the physical characteristics, such as shape and rigidity, of three-dimensional (3D) virtual objects" [Takizawa et al., 2017] and " provide real free and real touch sensations" [Yokokohji et al., 2003]. It is "capable of placing a part of itself, or its entirety, in an encountered location that allows the user to have the sensation of voluntarily eliciting haptic feedback with environment at a proper time and location" [Mercado et al., 2021].

In McNeely's definition [McNeely, 1993], RSD are to be used for CAD design. Yet, as they conceptually bring real objects to users, this is actually limited to exploration and manipulation tasks. In Yokokohji's definition of WYSIWYF displays [Yokokohji et al., 1999], they are used in training scenarios, and to improve visuo-motor skills, as these interfaces enable "a spatially and temporally consistent visuo-haptic feedback".

### 4.1.2 Classic Scenario

According to all of the previous definitions, I depict a classic scenario involving a Robotic Graphics interface (Figure 4.3). Let us picture a user in a virtual environment, wearing a Head Mounted Display.

"Matt enters a virtual room. He sees a table, on a corner of the room, on which are displayed a cylinder and a cube; and a cupboard, on which is displayed a pyramid. (1) He visually navigates through the environment, and (2) intends to interact with the ball. (3) The Robotic graphics interface anticipates this intention, and (4) moves towards the corresponding cylinder position in the physical world - to physically overlay it in the virtual one. (5) It changes its configuration to simulate a cylinder primitive. In the meantime, (6) Matt reaches for the cylinder. (7) He finally interacts with it with a great visuo-haptic consistency, both spatially and temporally."

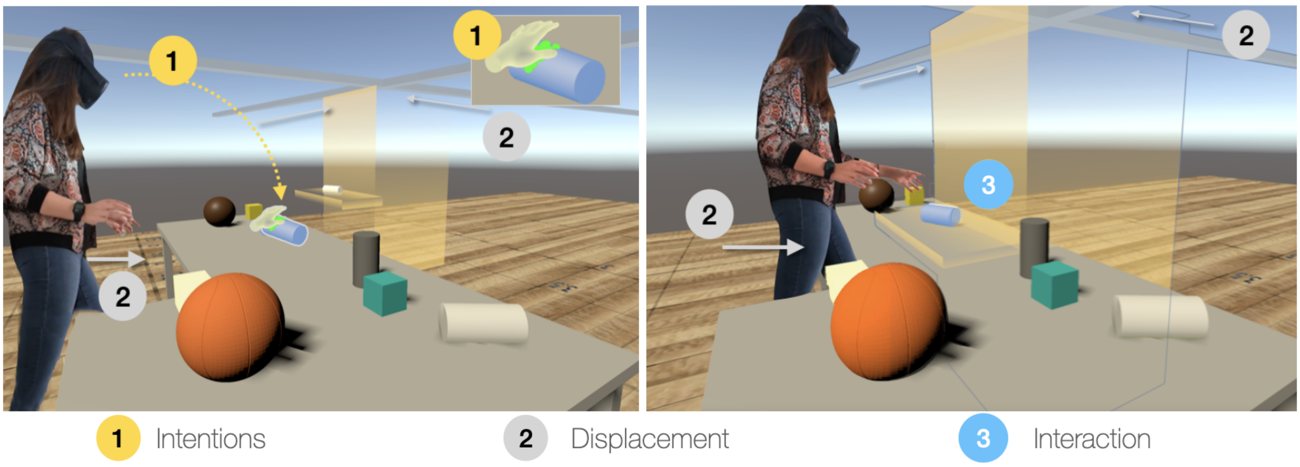



Figure 4.3: A Classic Robotic Graphics scenario: 1. Intentions, 2. Displacement, 3. Interaction.

This scenario can be interpreted from both the User and the Robot perspective (Figure 4.3).

1. *Intentions:* The user *intends* to interact, the robot *predicts* it.
2. *Displacement:* The user and the robot both *move towards the chosen object of interest*.
2.bis *Reconfiguration:* The interface potentially changes its end effector or reconfigures itself[3].
3. *Interaction:* Finally, the user *interacts* with the robot.

[3] The step number here is 2.bis as it is a type of *Displacement*.

In a classic scenario, users are hence free to interact with any object of interest with no regards to the scenario's progress. I define this experience as a *non-deterministic*[4]. Otherwise, I define the experience as *scenario-based*. These three bullet points are used to define our failure modes and effect analysis.

[4] It recently was referred to as an *unscripted experience* [Clarence et al., 2021].

## 4.2 Approach: Failures and Mitigations

In this chapter, we take root from the FMEA (*Failure Modes and Effects Analysis*) process in Industries and Product design.

*Definition* FMEA - *Failure Modes and Effects Analysis* - is a common approach in Industries and Product design. "“Failure modes” refer to the ways in which something might fail. Failures are any errors or defects, especially ones that affect the user, and can be potential or actual. “Effects analysis” refers to studying the consequences of those failures" [ASQ, 2021, Stamatis, 2003]. FMEA enables to better understand how to achieve a successful design and aims at enhancing a product reliability: it helps defining product specifications, as it analyses the main principal *functions* (or sub-functions) and requirements the product must achieve.

*Procedure* In order to use a Failure modes process, we use the product main function. We then depict it in *sub-functions*, identifying the "tasks" it *must* perform, and therefore translating it into product requirements. Among the functions, we then have a Troubleshooting phase where we identify all the potential failures, their causes and their effects.

The failures effects are usually rated in terms of severity (eg. an unsafe interface colliding with a high speed into a user will cause injuries) and probability of occurrence (eg. a slow robot is likely to not reach its target prior to interaction). The combination of these criteria enables designers to identify and rate the most critical failures (in a criticity matrix) to mitigate in their implementations.

*FMEA & ETHDs* We propose to use the FMEA approach to study ETHDs as transposing approaches from industry to research can foster the deployment "beyond the prototype" [Hodges, 2020, Khurana and Hodges, 2020]. We believe this approach can provide the necessary step back to improve the ETHD usability, by analysing and discussing the different failures designers must take into account when designing and implementing ETHD interfaces.

As we do not focus on a single design but on current literature designs and functionalities, and their associated mitigation solutions, we thus do not provide the criticity information.

We separate the failures in two categories: in the conception phase, and in the perception phase. The conception phase focuses on the failures from a *hardware* perspective, while the perception phase failures refer to discrepancies the users might *experience*. In the conception phase, we distinguish failure modes from a classic Encountered-type of Haptic Display scenario. We distinguish failure modes in the perception phase by analysing the different haptic features that can be stimulated. These two phases are not independent from each other and show some redundancy, yet depicting both of them offers a thorough and complete analysis.

## 4.3 Failures in the Conception Phase

In the conception phase, we focus on the steps 1-2 from our classic scenario (Figure 4.3). We understand that for the interaction to occur, the robot needs to be displaced *prior* to interaction. The first step in the FMEA process is to discretize this *function* in sub-functions and requirements. The second step in the FMEA process is to identify the failures causes and effects. The last step consists in defining how to mitigate these failures.

The sub-functions and requirements in this scenario steps are:

*Intentions* The robot *must* anticipate which object of interest to overlay (prediction algorithm resolution).

*Displacement*
- The robot *must* reach the chosen object prior to the user (speed requirement).
- The robot *must* reach the chosen object accurately (accuracy requirement) and reliably (precision requirement).
- The robot *must* avoid the user during its displacement (safety requirement).

*Reconfiguration* Finally, the robot *must* display the adequate prop, adequate end-effector or reconfigure itself with the adequate shape.

### 4.3.1 Predicting the Users Next Interactions - Step 1

*Failure Causes*

Predicting the users next objects of interest can be perceived from an arena to a desktop scale. In an arena, the algorithm is required to anticipate the future object of interest within a walking delay, while at a desktop scale, the algorithm is required to anticipate it within a reach-to-touch phase. These delays might be too short for the algorithm to predict the targets. They are for instance measured in Unscripted retargeting [Clarence et al., 2021], which studies the algorithm target acquisition accuracy as a function of the reach-to-touch movement (81% accuracy of correct target acquisition at 65% of the movement). Moreover, as ETHD are often designed to enable bare-hands and unencumbered interactions, a lack of information from the users can complicate the prediction, as the input for prediction models should rely on the users behaviours. For instance, intention prediction models can involve gaze and hand coordination, which hence require both an eye and a hand-tracker [Binsted et al., 2001].

The parameters that can change a prediction algorithm resolution are: (a) the number of virtual objects of interest; (b) the distance between them; (c) their respective sizes. The more objects available for interactions, the better resolution the algorithm must display. Similarly, the smaller the objects, the better resolution must be. Therefore, proposing a large number of objects and/or of small sizes and/or close to each other can cause failures in the prediction.

The algorithm inputs can also cause a failure: we can potentially imagine an algorithm relying on users' gestures or behaviours. The algorithm would require enough robustness to cater for unexpected movements or brutal gestures.

### *Failure Effects*

The effect of this failure is simple: if the algorithm does not predict the future target, the robot cannot physically overlay it, and the interaction cannot occur. When the prediction is correct but the delay is too short, this results in a failure in the displacement of the interface and ultimately in the overlaying of the virtual object with a physical prop.

### *Solutions for Mitigation*

An obvious solution for mitigating a failure in the prediction algorithm would be to rely on scenario-based experience, such as with the *Beyond the force* drone experience [Abtahi et al., 2019]: the robot does not need to anticipate the users' behaviours, as the full experience is scripted.

Instead of determining which object of interest is about to be interacted with - which thus also removes this intention prediction step, interfaces can also follow the users directly and stop whenever the user touches them. This requires sufficient speed and safety measures to avoid any collision. These interfaces are referred to as *Encounter-type* of haptic displays [Gonzalez, 2015]. They differ from ETHD (Encounter**ed**-type of haptic displays) as they do not anticipate the users movements but follow them from a small distance. Theoretically, when their speed is sufficient, these interfaces can cater for unexpected movements from the users as they remain at a constant distance from them and within their vicinity.

In the same regards, the robot can also overlay the closest object from the users' hand. It follows the users and overlays the closest objects from their vicinity. This is for instance implemented with the Snake Charmer [Araujo et al., 2016] robotic arm (see Figure 4.4).

Figure 4.4: Snake Charmer [Araujo et al., 2016]: The robotic arm overlays the closest object from the user's hand.

Zoomwalls only considers users with a walking speed below $0.4m/s$ [Yixian et al., 2020] to ensure this delay is long enough. It employs a swarm of mobile robots to overlay virtual walls with physical ones (see Figure 4.5), and assigns a different role to each of them. It distinguishes the *Active*, *Standby* and *Dispatched* ones. All of the Standby robots are following the user. When an interaction decision is made, the closest Standby robot becomes the Dispatched one. Once it reaches the interaction position, it then becomes Active.

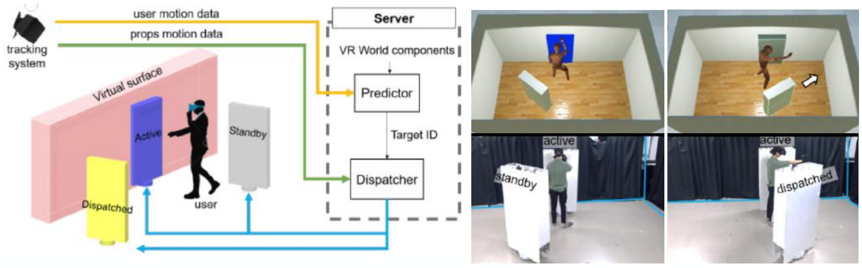



Figure 4.5: ZoomWalls [Yixian et al., 2020] Active, Standby and Dispatched walls.

Increasing the number of robots to overlay the closest objects is a good alternative to refining an intention prediction model. This was implemented in VRRobot, which uses three robotic arms around the user [Vonach et al., 2017], and with Roomshift (see Figure 4.6), where mobile robots move objects around the VR arena [Suzuki et al., 2020].

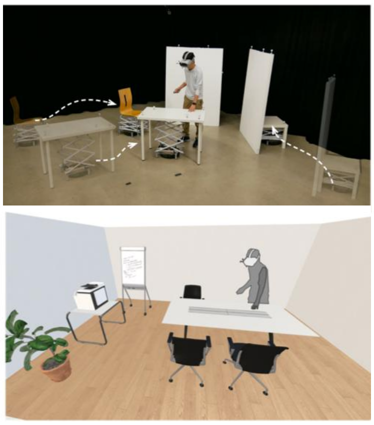


Figure 4.6: RoomShift [Suzuki et al., 2020]: Mobile Robots moving furniture around the VR arena.

Another solution is for designers to add *prior probabilities* to the non-deterministic experience: it is still unscripted, yet the algorithm decision phase is facilitated. For instance, if a basketball hoop and a ball were available for interaction, one can assume that the ball would be interacted with first. Instead of being equally available, the objects are weighted accordingly with the probability to be interacted with; the interface moves at the centroid of these weighted objects' positions. Finally, another alternative is to decrease the number of available props, and/or increase their sizes and/or their spacing.

### *4.3.2 Displacing the Interface - Step 2*

#### *Failure Causes*

The failures in the interface displacement can be speed, accuracy and safety related. Indeed, the interface trajectory generation must (a) avoid the user and any unwanted collision and (b) reach the target accurately (c) prior to the user.

Consequently, the causes for failures can be from a collision with the user, justifying that the dynamic trajectories are not generated correctly or do not take into account the users' displacements. The interface can potentially displace itself safely around the user but miss the target because of a lack of accuracy, speed, or because of an uncontrolled deceleration or even oscillations [Snape et al., 2011].

Regarding safety, we can also depict failures in the reachability of the interface (see Figure 4.7): either the object of interest to overlay can be too far from the interface's workspace centre (at its boundaries) and it can become inaccessible for the robot - because the user is blocking its access, by being too close from the object - or because the interface cannot reach the target without colliding with the user.

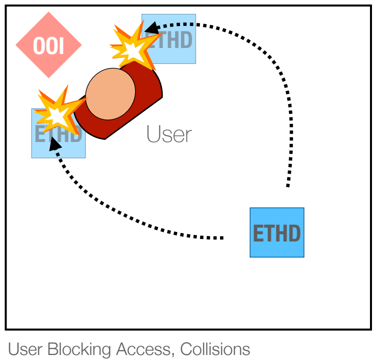



Figure 4.7: The ETHD interface cannot reach the Object of Interest because the user is blocking the access. This causes collisions and safe trajectories cannot be generated.

### *Failure Effects*

The most important criterion in the design of an experiment blending users with robotised interfaces is to ensure their safety. Therefore, an experiment with unsafe trajectory generations will not be able to be tested and even less deployed.

A lack of speed or accuracy can result in the interface not being available prior to the user, which compromises the interaction. A failure will cause what I define as a *spatial mismatch*: the interface is not physically overlaying its virtual counterpart because of its spatial position. Ultimately, the users would not be able to interact with their virtual environment with haptic feedback.

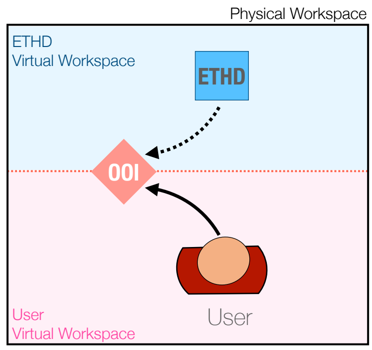



Figure 4.8: The physical workspace is split so the user and the ETHD do not collide with each other whilst displacing. If the user arrives before the ETHD, we can consider coupling this with other techniques such as the "color coding" in Figure 4.10.

### *Solutions for Mitigation*

Safety-wise, a good solution to mitigate the risks is to run simulations where the user would not be hurt. For instance, designers can record users doing the experiment without haptic feedback, to eventually run simulations with an avatar (simulated user) and real interfaces movements. Many different algorithms ensuring safe environments with dynamic movements of both the user and the interface are currently available. A solution is to employ algorithms usually developed for swarm interfaces, and to perceive the user as another interface, which must be avoided. The interfaces aim to reach the same goal whilst avoiding collisions with each other: indeed, the user and the interface share the same space [Kim and Follmer, 2021]. The global idea is to extract the positions and speeds of each interface, to determine its future positions and generate trajectories accordingly, oscillation and collision free. This principle is known as the *Velocity Obstacle* [Fiorini and Shiller, 1998], but has been improved as Reciprocal Velocity Obstacle [van den Berg et al., 2008] and Hybrid Reciprocal Velocity Obstacle [Snape et al., 2011]. Collision avoidance algorithms using artificial potential fields have also been developed for teleoperation and manipulators [Khatib, 1986, Kaldestad et al., 2014]: we can consider artificially representing the user as a high potential obstacle the robot must avoid.

The previous techniques all consider a shared space between the user and the robotised interface. Yet, in order to avoid collisions during the interface displacement, we can also consider distinguishing the user and the ETHD workspace (see Figure 4.8). The schematic drawing shows a top view of a VR arena, though we can consider this approach by working on different heights as well. This can be considered with drones, being in the air and thus offering interaction opportunities at various heights.

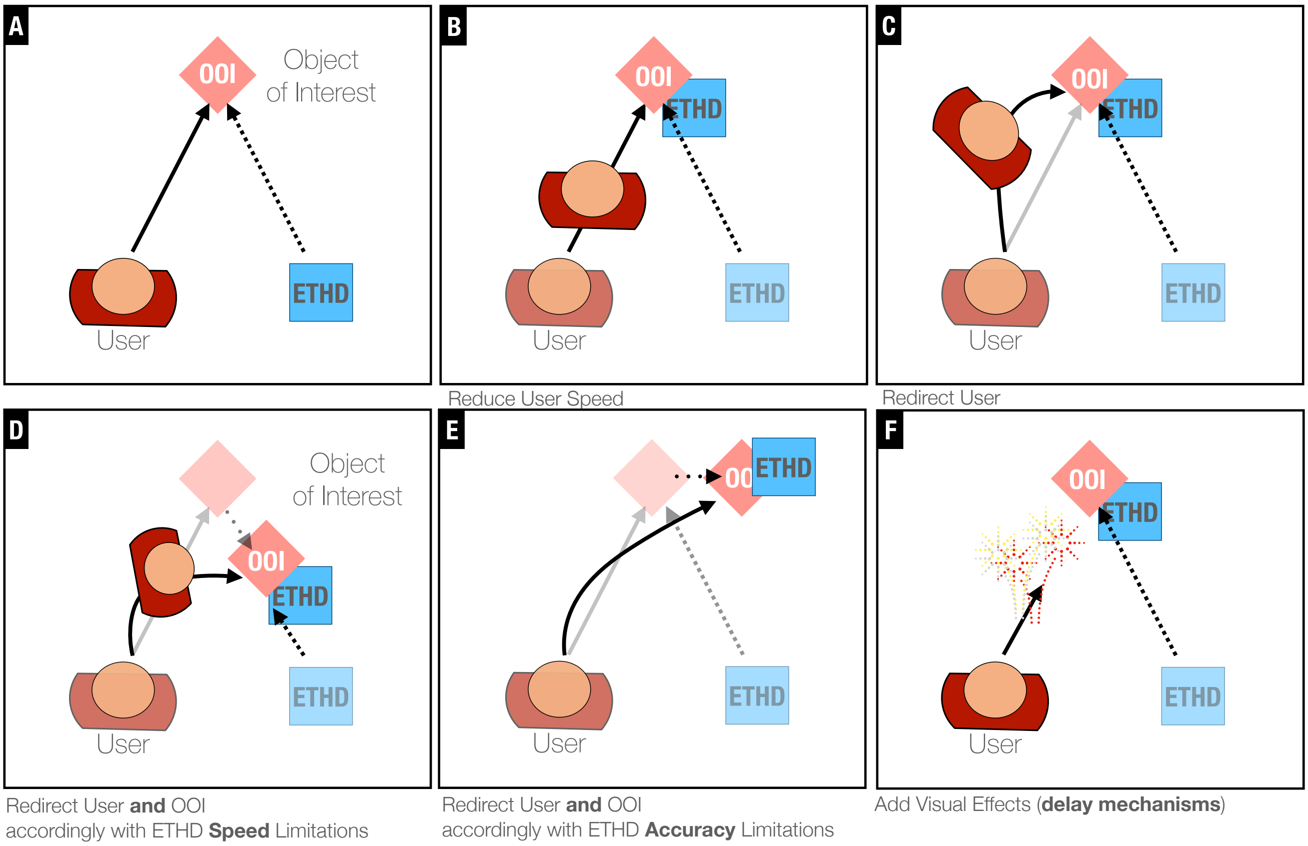



Figure 4.9: Solutions for Mitigating Displacement failures from Scenario A, the user and ETHD are at equidistance from the Object of Interest (OOI). B - The user speed is artificially reduced so the ETHD arrives prior to the user. C - The user trajectory is altered to give spare time for the interface to reach the OOI position. D - The user and the OOI position are redirected, to cater for ETHD speed limitations. E - The user and the OOI position are redirected, to cater for ETHD accuracy limitations. F - Visual effects (fireworks here) are added to delay the user, make him stop and give spare time for the interface to place itself.

Speed and Accuracy-wise, when the user and ETHD are equidistant from the Object of interest - OOI (Figure 4.9 - A), this means the ETHD displacement speed must be higher than the user's one. In ZoomWalls [Yixian et al., 2020], the user's speed is reduced by adding a disturbing noise (from the movie Predator) in the users headphones when it is above $0.4m/s$ (the maximum speed the interface can reach). Otherwise, the user trajectory can also be altered *visually*, using redirection techniques such as the *Redirected Walking* [Razzaque et al., 2001]. Therefore, it avoids the interface trajectory, whilst enabling it to keep the shortest pathway towards the target (Figure 4.9 - C).

Many ETHD interfaces suffer from accuracy and speed issues - mostly ungrounded ones such as mobile platforms or drones[5]. Redirecting techniques are hence used once again as *dynamic retargeting*: the user's future target is estimated, as well as the interaction time, based on a Jerk model [Gonzalez et al., 2020]. This estimation time then helps to predict the future position of the ETHD which suffers from speed limitations; the object of interest as well as the user are then redirected for a physical contact to occur (see Figure 4.9 - D). This also enables to perform experiences in *unconstrained virtual arenas* [Gonzalez et al., 2020].

[5] Note that these interfaces are also noisy and require users to wear noise-cancelling headphones.

Similarly, and as displayed in Figure 4.9 - E, ETHD such as [Abtahi et al., 2019] employ this *dynamic retargeting* for the users to physically encounter the ETHD despite its accuracy limitations.

Figure 4.10: "The patch is highlighted in green, indicating that the user can touch the virtual object." [Abtahi et al., 2019]

A Wizard-of-Oz implementation of Robotic Graphics called *TurkDeck* - "Human actuators" are transporting props around the users, instead of a robotised interface - demonstrated techniques to avoid both safety and accuracy/speed issues [Cheng et al., 2015]. They add visual effects to act as **delay mechanisms** (Figure 4.9 - F), and give some spare time for the human actuators to place themselves adequately.

In the same regards, visual aids can be added to ask the user to wait for the object to be ready for interaction. A color code eventually informs the user that the interaction can occur (see Figure 4.10) [Abtahi et al., 2019].

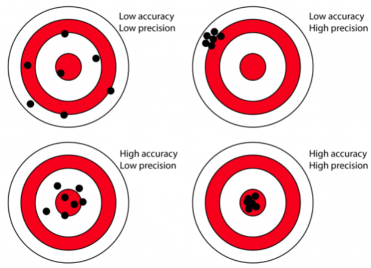



Figure 4.11: Accuracy vs Precision [Davies].

As mentioned in the previous subsection, we suggest the designer adapt their virtual environment: while the accuracy of the algorithm could be improved by modifying the OOI's number, sizes or spacing, designers can anticipate their interfaces' issues and add visual effects with no regards of its current capabilities. This can also be useful whenever the interface shows no repeatable/precision hardware capabilities (see Figure 4.11).

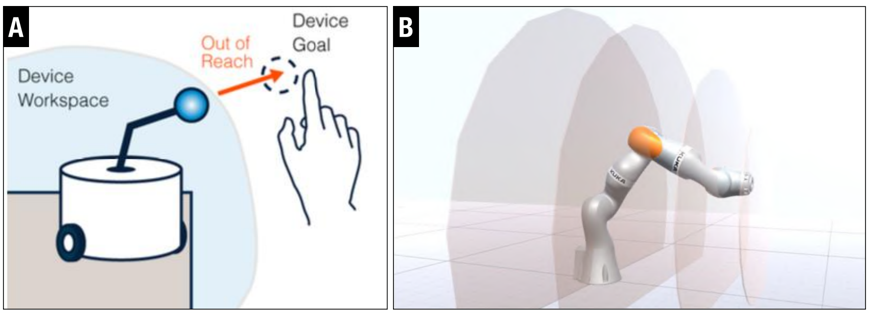



Figure 4.12: A. Schematic of an ETHD having reachability issues: the device goal is out of reach (from [Gonzalez et al., 2020]). B. Four per-plane reachability maps of a Kuka robot, from [Kim et al., 2018].

Moreover, if the scene design shows objects of interest outside of the interface workspace, which is called a *reachability issue* (see Figure 4.12 - A) [Gonzalez et al., 2020], the designer can establish reachability planes from the beginning on the experiment design and only offer interaction opportunities within this workspace. In H-Wall [Kim et al., 2018] for instance, per-planes reachability maps of a Kuka robotic arm with an end-effector were simulated prior to the design of the user experience (Figure 4.12). Virtual objects were then to be placed within this workspace.

### 4.3.3 Modifying the End-Effector Configuration - Step 2.bis

For the interaction to occur, the ETHD either provides the user with a real object, modifies its end-effector or reconfigures itself (Figure 4.13). A modification of end-effector consists in changing the interactable prop (*between* various objects) while a reconfiguration consist of changing its shape (*within* the object). The end-effector can also be referred to as a *SAD - Shape Approximation Device* [Hoshino, 1995]. It can be composed of various edges and shape primitives [Hoshino, 1995], textures or objects [Araujo et al., 2016].

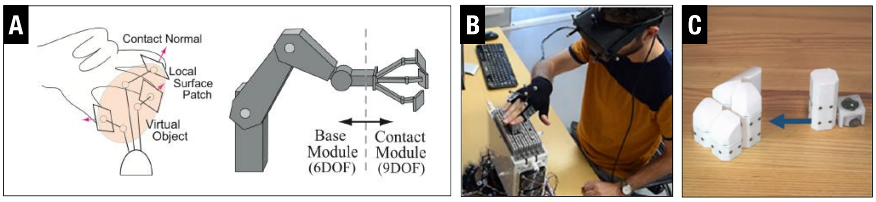



Figure 4.13: Interfaces reconfiguring themselves for interaction. A. Shape-Changing End-Effector for multiple fingertips, from [Shigeta et al., 2007, Yokokohji et al., 2005]. B. 2.5D Tabletop, from [Siu et al., 2018]. C. Reconfigurable robotic elements (roboxels), from [Zhao and Follmer, 2018].

#### *Failure Causes*

An ETHD displacing multiple objects can display the wrong one for interaction, yet this is once again a failure in the interface's displacement/accuracy (see previous subsection).

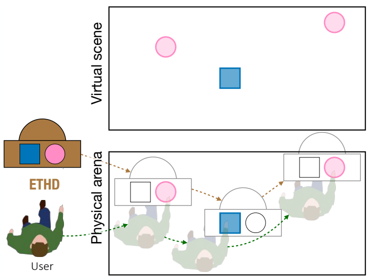



Figure 4.14: A robotic shape display enabling a 1:1 and a 2:1 <*virtual:physical*> *mappings*.

The wrong primitive or object can be displayed or simulated - when using shape-changing devices such as Figure 4.13 - A [Yokokohji et al., 2005, Shigeta et al., 2007], 2.5D Tabletops [Siu et al., 2018] (Figure 4.13 - B) or Roboxels (reconfigurable robotic elements) such as [Zhao and Follmer, 2018] (Figure 4.13 - C). This can be caused by the interfaces resolution. For instance, the 2.5D Tabletop (Figure 4.13 - B) aimed for a 1.25mm resolution - based on two-point tactile acuity from [Bruns et al., 2014] - but chose to display a 7mm resolution for design simplicity purposes; while the end-effectors in Figure 4.13 - A display in reality 30mm contact modules.

Beyond the interfaces' resolution and depending on the tasks users are to be performing, a failure can also occur as these interfaces usually physically overlay a part of the virtual object, but not the object in its entirety. For instance, the multi-finger interface Figure 4.13 - A is sufficient to explore an object shape through three fingers, but it is not able to cover the palm or the hand in its entirety in a manipulation task.

*Failure Effects*

I define a Failure in the end-effector reconfiguration as a *shape mismatch*: the interface is not physically overlaying its virtual counterpart because of its shape. This can result in a *semantic violation* (defined in Chapter 2) [6]: a discomfort due to a discrepancy in the visual expectations and the associated haptic feedback.

[6] It is a discrepancy which violates the human body semantics and is heavily rejected by users [Rodriguez-Fornells, 2015]

*Solutions for Mitigation*

A first solution to mitigate this effect is to limit the users tasks, objects of interest variety or shape complexities within the VR scene. In his conceptual definition of Robotic Shape Displays, McNeely already provided a critic in these regards:

> *"RSD would work best in VR scenarios where the objects are of fixed size and appear repetitively, for example, interacting with a virtual radio's layout of knobs, switches and buttons. It is felt that a large number of useful applications, in manufacturing design, and design verification, are amenable to this approach with existing technology."* [McNeely, 1993]

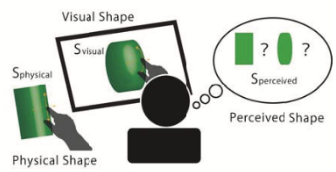



Figure 4.15: Experiment of Pseudo-Haptic experiment from [Ban et al., 2012].

McNeely hence suggests using *<virtual:physical> mappings* (Figure 4.14): as a thorough 1:1 mapping is more complex to build, a physical object can for instance overlay multiple virtual ones [He et al., 2017].

Ever since McNeely's definition, advances in Pseudo-Haptics[7] (see Chapter 3) demonstrated that objects of approximately similar primitives can be used to simulate the same object, without altering the user's perception.

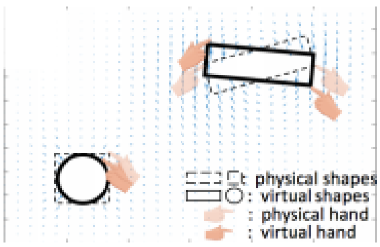



Figure 4.16: Redirection and Pseudo-Haptics enabling the exploration of complex boundaries [Zhao and Follmer, 2018].

[7] Pseudo-Haptics leverage the users visual dominance over haptics to alter their perception.

This hence also simplifies the use of the previously suggested mappings *shape-wise*: a simple cylinder can either represent a cylinder, a cone, or even a sandglass [Ban et al., 2012] (Figure 4.15). Similarly, redirection and pseudo-haptic techniques can be used to enable the exploration of complex objects using simple props [Zhao and Follmer, 2018] (Figure 4.16).

Finally, for shape-changing devices, designers can also alter their virtual scene to match their devices resolution. This can be perceived as a limitations in the usability of these devices. For instance, shapeShift [Siu et al., 2018] and the device from [Yokokohji et al., 2005] do not show the same level of details to represent a ball, as seen in Figure 4.17.

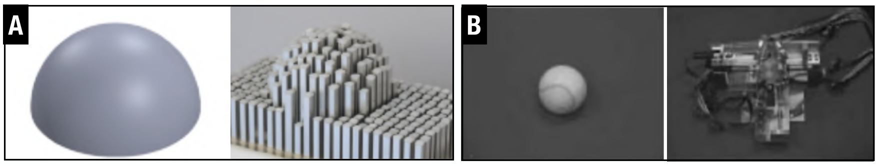



Figure 4.17: A. High-resolution pin array representing half a ball to explore [Siu et al., 2018]. B. Contact modules representing a ball through 3 fingers [Yokokohji et al., 2005].

We explored the different Failure modes, causes, effects and mitigation solutions in the Conception phase of an ETHD interface and its associated virtual environment. Yet, we can notice that all of the previously evoked effects are user experience-related. Indeed, every conception failure and design challenge has a direct consequence on the user experience.
This section is oriented with a *Haptic Solution* perspective (from our triangular approach). The next section is oriented with a *Haptic Feedback* and a *Haptic Interaction Techniques* perspective: we identify the different failures in the Perception phase of the ETHD scenario, ie during the interaction.
We define the haptic feedback associated with interaction techniques and depict the perception discrepancies that might occur when interacting with an ETHD.

## 4.4 Failures in the Perception Phase

In this section, we focus on the Interaction step #3 of the ETHD classic scenario (Figure 4.3 - 3): when the contact does occur and the haptic feedback is provided.

We associate Haptic feedback with Haptic Interaction techniques in this section. In these regards, Lederman associated Object properties (from a Haptic feedback perspective) with Exploratory procedures (from an Interaction perspective) [Lederman and Klatzky, 1987]. An "Exploratory Procedure" is defined as "stereotyped movement pattern having certain characteristics that are invariant and others that are highly typical. It needs not correspond to a particular configuration of the hand, a fixed pressure, or a particular end-effector" (see Table 4.1).

Table 4.1: Object Properties and associated "Exploratory Procedures" [Lederman and Klatzky, 1987].

| Object Property | Exploratory Procedure |
|---|---|
| *Substance-related properties* | |
| Texture | Lateral Motion |
| Hardness | Pressure |
| Temperature | Static contact |
| Weight | Unsupported Holding |
| *Structure-related properties* | |
| Weight | Unsupported holding |
| Volume | Enclosure, contour following |
| Global shape | Enclosure |
| Exact shape | Contour following |

We can exploit these exploratory procedures to analyse the different failure modes *perception-wise*: we assume that a *semantic violation* might occur and damage the haptic experience in VR when they are not correctly simulated, as outlined in Chapter 2. We distinguish the Substance-related properties from the Structure-related ones in the following sections.

### *4.4.1 Objects' Substance-related Properties*

#### *Failure Causes*

Going through the different exploratory procedures in Table 4.1, we can start with the *"Lateral motion"*. A failure can for instance be perceived in the infinite exploration of a wall. Haptically speaking, this motion results in a **tactile slippage** of the skin. Yet, some interfaces enable this infinite exploration whilst moving the interface accordingly with the user's displacements ([Araujo et al., 2016, Yixian et al., 2020]): the slippage cannot occur.

A failure in the applied *"pressure"* corresponds to a discrepancy in the users' **perceived stiffness** through kinesthetic feedback. This can be translated as an ETHD robustness requirement. Indeed, while robustness is perceived as a *hardware requirement* in Chapter 3, it is in fact only required in the third step of the ETHD classic scenario ("Interaction", Figure 4.3 - 3). For instance, if a user is to lean or push on a wall, the ETHD is required to handle this pressure and to react accordingly (eg stay still). Yet, this is a common failure with ungrounded solutions such as mobile robots or drones, which struggle to compensate for the users applied forces in order to replicate the expected hardness.

For temperature-related failures, a study demonstrated that when heat is visually stimulated in an object (a teacup with a fuming beverage for instance), users tend to interact from a cooler location over the object (eg the teacup handle) [Blaga et al., 2020]. Yet, if they do interact over the teacup base, they might be expecting a hotter temperature.

For a user to perceive a correct *weight*, the object of interest is required to be held whilst being unsupported. A common failure of this procedure is known as the **lack of haptic transparency**. The fully transparent haptic device is "an imaginary massless and infinitely rigid stick" [Hayward and Maclean, 2007], which enables the exploration and manipulation of the virtual object without any inertia or friction effect. This failure hence occurs whenever the users are not enabled to perform "a free object manipulation". It can be identified in [Abtahi et al., 2019] for instance: when the drone is active, its thrust adds a supplementary weight, and friction effect when holding a prop; when the drone is inactive, its weight will be added to all of the objects attached to it in an unsupported holding.

### *Failure Effects*

All of the previously listed failures result in a discrepancy from the users expected haptic feedback (in textures, forces, weights, temperatures). For instance, tactile slippage usually enables the user to haptically distinguish textures [Degraen et al., 2019]. Thus, the Lateral motion failure will impact the texture perception. Similarly, perceived stiffness and haptic transparency will respectively impact the hardness and weight perception during the experience.

### *Solutions for Mitigation*

Two solutions are currently investigated to mitigate the lateral motion failure. The first one consists in using swarms of interfaces (at least two [Yixian et al., 2020, Siu et al., 2018]) than can place themselves in a continuous manner for users to perceive the correct slippage (see Figure 4.18 - A). The second solution is to move the interface as a function of the users motion direction [Mercado et al., 2021] (see Figure 4.18 - B).

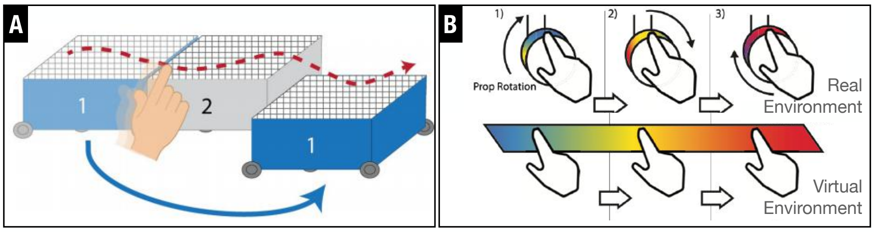



Figure 4.18: A. Swarms of Interfaces to display a continuous surface to explore. B. Prop rotation enabling to perceive textures.

Similarly, as mobile interfaces struggle to display adequate perceived stiffness, they can for instance move in the opposite direction of the users' applied forces, to replicate the expected hardness.

Temperature-wise, apart from designing room-temperature experiences, we can integrate Peltier cells or heaters [Shaw et al., 2019] to physically replicate the adequate temperature expectations. Suggestions regarding where the users should explore the objects (for instance by the handle of a hot teacup rather than by its base) can also be integrated visually in the virtual experience.

Finally, weight-wise, the easiest solution is to exploit real objects or props and to literally display them to the users. This removes the haptic transparency specification from the interface design, as the prop itself is being manipulated.

### 4.4.2 *Objects' Structure-related Properties*

#### *Failure Causes*

Weight in the structural properties of an object is different from its absolute weight (in the substance-related properties): it corresponds to the inertia one can perceive when manipulating an object. We can identify this failure with on-demand handhelds [de Tinguy et al., 2020, Kovacs et al., 2020] (Figure 4.19), where the manipulated object's absolute weight is adequate, yet it generates an inertia in its displacement. Prior to holding the apple, the on-demand handheld provides an unexpected kinesthetic feedback, which alters the perception.

Figure 4.19: On-demand Handheld, simulating catching an apple [Kovacs et al., 2020].

Regarding enclosure and contour following for volumes and shapes (Figure 4.20 - A), we can find a failure for exploration and manipulation tasks (defined in Chapter 3.1). For instance, it includes users touching the edge of a shape approximation device while exploring an object, as the object's enclosure is not fully available (Figure 4.20 - B): the user explore the shoe at a given location, yet if he moves towards the shoe curvature, a discrepancy will occur.

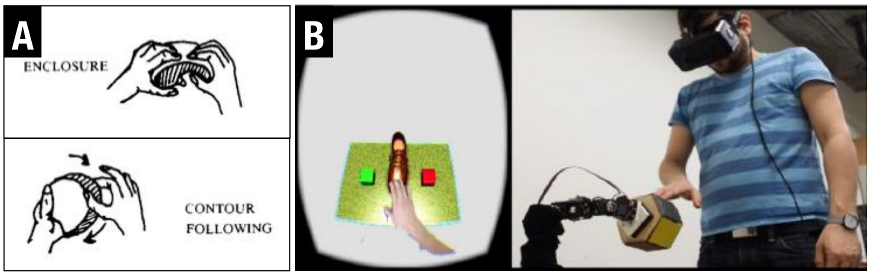



Figure 4.20: A. Schematics of Enclosure and Contour Following from [Lederman and Klatzky, 1987]. B. A User exploring a shoe material with Snake Charmer [Araujo et al., 2016]: if the user moves, he will perceive the edges of the Shape-approximation device; the shoe is not available interaction-wise for Enclosure or Contour following Exploratory procedures.

#### *Failure Effects*

Structural discrepancies in the object properties (weight, volume, shape-wise) can potentially mitigate the user experience, at both tactile and kinesthetic levels. Besides, being able to manipulate objects, control and act on the virtual environment, is important to correctly feel immersed [Witmer and Singer, 1998].

#### *Solutions for Mitigation*

In the same regards as with the Objects' Substance-related properties (previous subsection), these failures can potentially all be removed through the use of real and untethered objects. Yet, it is costly to have a multitude of objects to be displayed, especially in their entirety (to cater for the global and exact shape requirements). One solution could be to use objects of approximately the same sizes and primitives in the design of the VR scene [Hettiarachchi and Wigdor, 2016], and to rely on the users' vision to alleviate their haptic perception (similarly as Section 4.3.3). Otherwise, designing the VR scene accordingly with the available props is a common technique: in the design of the on-demand handheld Figure 4.19, only spherical objects are available for interactions.

Figure 4.21: A shifting weight interface called SWISH [Sagheb et al., 2019].

Mitigating the "weight" failures in the objects' structural properties can be achieved through the integration of weight-shifting modules within the ETHD. We can for instance imagine taking root from variable elastic stiffness [Achibet et al., 2015], and attach the objects on the ETHD interfaces with an elastic of variable stiffness. Thus, the same object could be perceived with different weights. We can potentially take root from [Sagheb et al., 2019] (Figure 4.21) to integrate motors and actuators within the simulated objects, to relocate their centres of gravity and enable the user to perceive variable inertia using the same original prop.

## *4.5 Conclusion*

In this chapter, we provided an analysis of Robotic Graphics interfaces, lately referred to as Encountered-type of Haptic devices, through their Failure modes. This approach provides a groundwork for designers aiming to conceive these interfaces.

We depicted a classic scenario involving such an interface, and identified the potential interfaces' failures modes, their associated effects and the solutions to mitigate them. We showed how all of the designer Conception failures impacted the user Perception phase. We also identified the different failures in the perception phase, that might alter the users experience: we analysed the various exploratory procedures users perform and identified these failures in the provided haptic feedback. Once again, we found that these failures can be mitigated through interface's design changes. The different failures are summarized in the following table (**Table 4.2**), with regards to the classic ETHD scenario.

This chapter is to be used as a foundation for the development of ETHD interfaces: it identifies their primary functions, and therefore helps to define their specifications.

In this first part of the dissertation (Part I), we first provided background on integrating Haptics in VR experiences (Chapter 2). Chapter 3 helped to identify the interaction opportunities in VR, and emphasized the potential of Robotic Graphics interfaces. In this chapter (Chapter 4), we pursued the Robotic Graphics analysis to understand their requirements and help defining their specifications. In the next Part of this dissertation (Part II), I focus on the conception of an ETHD interface. Its requirements are[8]:

[8] A reminder of the scenario is in displayed in Figure 4.22.

Table 4.2: Potential Failures Modes associated to Encountered-type of Haptic Displays, in the Conception and Perception phases.

| Conception Phase | Perception Phase |
|---|---|
| *Haptic Solution* | *Haptic Feedback & Interactions* |
| **Intentions - Step 1** | **Interaction - Step 3** |
| Algorithm success rate | Tactile slippage |
| Algorithm delay | Perceived stiffness |
| Algorithm resolution | Temperature |
| **Displacement - Step 2** | Haptic transparency |
| Safety (Collisions) | Inertia |
| Speed | |
| Accuracy | |
| Precision | |
| **Reconfiguration - Step 2.bis** | |
| Resolution | |
| Shape Mismatch | |

*Intentions* An algorithm which predicts the users next interaction absolute location, **within an object** when a single object of interest is available (*resolution requirement)*, **prior to contact** (*algorithm delay*). This will be implemented in Chapter 5. It must also identify which primitive to overlay. The algorithm must also enable non-deterministic scenarios when multiple objects of interest are available **within the scene** (*success rate requirement)*: this algorithm will be a compromise with the interface's mechanical design. This will be developed in Chapter 6.

*Displacement* The interface will be required to generate *safe* trajectories around the user, and to avoid any unexpected collisions. With a sufficient *speed and accuracy*, and a reliable and *precise* control scheme, we will investigate whether a mitigation strategy will be required. This will be developed in Chapter 6.
*Reconfiguration:* The interface will be required to be modular (see Chapter 3) with various props available to be displayed, **or** will display a shape-changing end-effector replicating the *desired* shapes of interest.

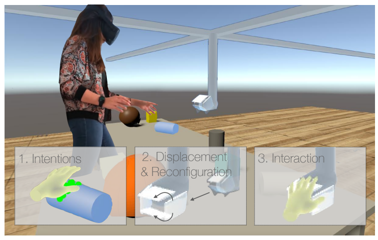



Figure 4.22: An Encountered-Type of Haptic Device scenario: 1. Intentions, 2. Displacement & Reconfiguration, 3. Interaction.

*Interaction* From Chapter 3, we will require a large workspace for Navigation; the use of real objects for Exploration, Manipulation; and a high robustness for Whole-body interactions. From this chapter with a Haptic feedback perspective, real objects will enable *haptic transparency* and *inertia*, while robustness will enable *high perceived stiffness*. Our interface's design space, interaction opportunities and user evaluation will be described in Chapter 7.

WHAT YOU MUST REMEMBER

*Positioning:*

- Robotic Graphics are lately referred to as Encountered-type of Haptic Displays: they literally encounter the users at their object of interest with an adequate feedback.
- An ETHD scenario is realised through three main steps, (1) Intentions, (2) Displacement, (3) Interactions. This is valid from both the user and the robotised interface perspective.

*Contributions:*

- An analysis of ETHD through a QC & product design approach (*FMEA, Failure Modes and Effects Analysis*), and a framework to identify their conception and perception challenges.
- A groundwork for the conception, implementation and evaluation of ETHDs, and their global specifications.

# Part II

# CoVR: Conception, Implementation, Evaluation

# 5

# Within-Object User Intention Prediction Model

This second part is based on our previous Analytical Framework (Part I). It introduces a Robotised Tangible interface called **CoVR**, anticipating the users' intentions to encounter them with the appropriate feedback.

In order to implement CoVR, I first exploit the Robotic Graphics classic scenario from Chapter 4: the interface must predict the users next interaction intention location, to eventually displace itself and physically overlay the correct virtual counterpart. Finding out the absolute future contact location over an object of interest ultimately also enables the extraction of the local haptic features (shape, texture etc). In the subsequent chapters of this part of the dissertation (Part II), I will then define CoVR's hardware design and its use with multiple objects of interest (between-objects) (Chapter 6) and the interaction opportunities it offers (Chapter 7).

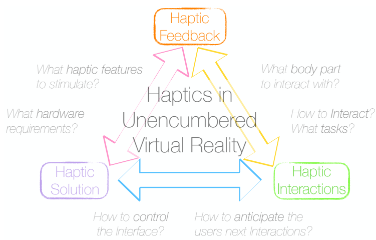



Figure 5.1: Reminder of our three categories and their associated research questions.

I focus in this chapter on bare-hands **haptic interactions** with fine hand-scale **haptic feedback**, from our introductory triangular approach (Figure 5.1) for Haptics in Unencumbered Interactions in VR. This chapter provides a model *predicting* the future contact locations *within* an object of interest, *prior* to interaction. It targets the *algorithm resolution and delay* specifications of Encountered-type Haptic Displays

(ETHDs) from Chapter 4, and therefore aims to improve the haptic fidelity of hand-scale interaction opportunities such as Exploration, Manipulation or Edition tasks (cf Chapter 3).

## *5.1 Motivations*

This model is destined to designers, but its ultimate aim is to facilitate the deployment of unencumbered interactions with haptic feedback in Virtual Environments. The global idea is to provide a software brick for Robotic Graphics [McNeely, 1993] interfaces. Anticipating the users' future contact locations provides *shape* information (and to an extent, local textures etc) for the interface to provide feedback and *positions* for the interface to reach.

In this chapter, let us consider a virtual environment with a single object of interest. The main question here is: *Where are the users going to interact* ***within*** *the object of interest?* The object is considered as multiple sub-objects, such as in [Shigeta et al., 2007]: a combination of various smaller objects, of various shapes and positions.

The Robotic Graphics interfaces will hence be soliciting the *software brick* to know **which** sub-object to display, or even to simulate (Figure 5.2 - A,B) and **where**. The motivations behind this work are to ultimately enable **non-deterministic scenarios** with realistic haptic feedback in VR, whether the interface is displaying primitives, simulating shapes, or displaying real objects (see Chapter 4 - *Reconfiguration*). Many Robotic Graphics interfaces seem promising, though they only enable scripted experiences. The idea is to provide a replicable and most of all, usable model to simplify providing haptic feedback using Robotic Graphics, whether they display (sub-)objects (Figure 5.2 - A) or reproduce them (Figure 5.2 - B).

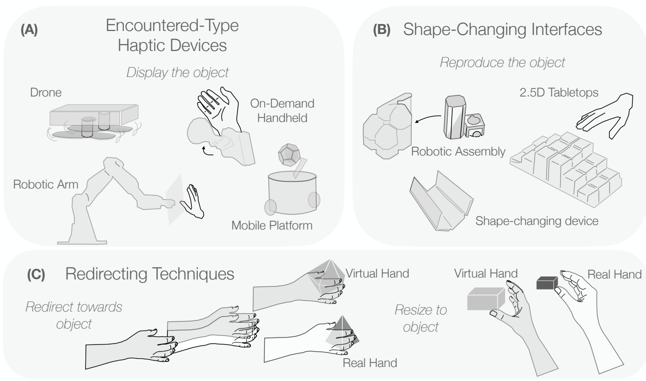



Figure 5.2: Different classes of technologies that benefit from our model to predict future contact locations within objects: Robotic Graphics interface can (A) *Display* the chosen object (with Encountered-Type of Haptic Devices, such as drones [Abtahi et al., 2019]; mobile platform [He et al., 2017]; on-demand handheld [de Tinguy et al., 2020]; robotic arm [Kim et al., 2018]) or (B) *Reproduce* the chosen object (Shape-Changing interfaces; robotic assembly [Zhao et al., 2017]; 2.5D tabletop [Follmer et al., 2013]). (C) Redirection techniques can also be applied to redirect the user hand towards the correct object [Kohli, 2010] or can be exploited to resize the grasp [Bergström et al., 2019].

This model can also be used with redirection techniques such as *"Haptic Retargeting"* [Azmandian et al., 2016], which were defined in the previous chapter as a common mitigation solution for various Robotic Graphics Conception related failure modes (Figure 5.2 - C). We can indeed extract the future contact zone, to modify the users' hand trajectory so it can meet a physical primitive of a similar geometry. This can even help with resizing grasps [Bergström et al., 2019] (Figure 5.2 - C): the virtual and real world interactions with objects can be matched together prior to contact; both the *real physical hand* and the *virtual redirected hand* enter in contact with the object simultaneously - thus haptic cues are correctly integrated in the experience. Similarly, to avoid Perception related failure modes, and as the hand is actually sensitive to surface contacts and edges, this can also help with a redirection at the exact location of interest, over surfaces or edges.

A recent paper depicted success criteria for Haptic proxies in VR: Sufficient similarities (with respect to haptic properties, eg size, shape) and Complete co-location (correct alignment of real and virtual proxies) [Nilsson et al., 2021] (see Figure 5.3). Our model provides the location information prior to interaction and can extract its haptic properties, for both these criteria to be fulfilled.

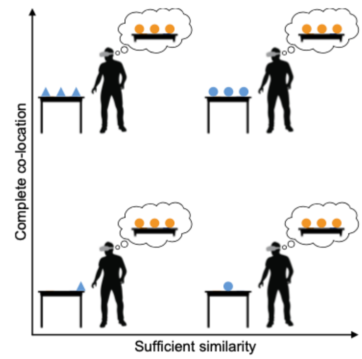



Figure 5.3: Success Criteria from [Nilsson et al., 2021]: Complete co-location and sufficient similarity.

- At a *Haptic Interactions* and *Haptic Feedback* intersection, the prediction is to be used for hand-scale interactions with bare-hands. Bare-hands interactions usually involve 3D volumes with irregular surfaces, depth, various shapes and primitives, which can potentially result in perception failures (cf Chapter 4). Providing this information is hence crucial to provide the adequate haptic feedback to each hand individual parts (thumb, fingers, palm).
- At a *Haptic Solution* and *Haptic Interactions* intersection, this prediction can be used position-wise: anticipating the future contact locations provides a control position that can be used in a future ETHD interface hardware.
- At a *Haptic Solution* and *Haptic Feedback* intersection, this prediction can be used shape-wise in a future ETHD interface hardware: the local primitive in the future contact point vicinity can be extracted[1], for the adequate feedback to be provided.

[1] As well as its local substance properties [Lederman and Klatzky, 1987].

## 5.2 Approach

Researchers and developers in Virtual Reality often refer to VR interactions as "being natural". In these regards, I decided to take root from **real world** hands behaviours, and most importantly, real interactions. Real bare-hands interactions are for most parts represented in grasp taxonomies: they indeed depict and describe many kinds of hand/fingers configurations for manipulating objects. My approach is hence to take root from these taxonomies, and the users' real hands *(inputs)*, to exploit them into a model that could provide future contact locations *(outputs)* (see Figure 5.4).

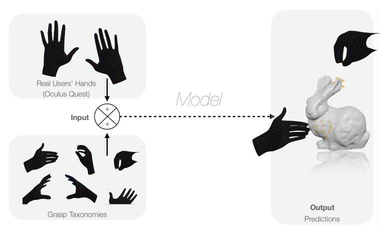



Figure 5.4: Inputs and Outputs of our Model.

## 5.3 Understanding Grasp

Feix [Feix et al., 2016] defined a grasp as "every static hand posture with which an object can be held securely, irrespective of the hand orientation". A manipulation task is the modification of an object position or orientation, and hence requires a grasp to be performed beforehand.

Grasp is task and object dependent [Napier, 1956, Becchio et al., 2012] - a bottle will be grasped differently whether a user want to drink it or to transmit it to someone else - yet, it still can be discriminated based on hand configurations.

Many grasp taxonomies have been drawn [Cutkosky, 1989, Kamakura et al., 1980, Gonzalez et al., 2013, Napier, 1956], using object types or sizes. A systematic review of grasp taxonomies was depicted by Feix et al. in 2016, as the "GRASP Taxonomy", resulting in 33 coherent human hand configurations, according to 4 properties: (1) Virtual fingers, (2) Grasp types, (3) Opposition space, (4) Thumb position. We will define these properties as a basis to develop a human-centered model for grasp.

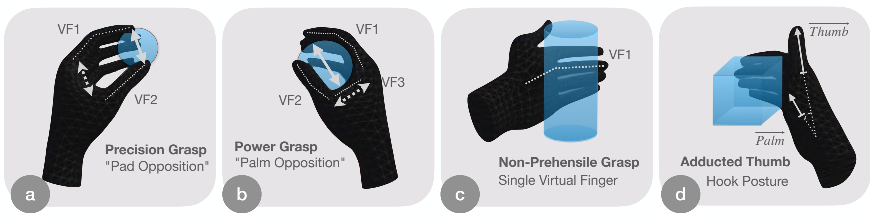



Figure 5.5: Illustrations of some definitions from the literature [Feix et al., 2016]: Virtual Fingers - VFs - are an abstract representation of fingers applying forces in the same direction and working as a unit. (a) Precision Grasp with Pad Opposition: the hand surfaces are parallel to the palm direction (dotted arrow). (b) Power Grasp: there is a rigid relationship between the object and the hand. The grasp is performed with a Palm Opposition: the hand surfaces are perpendicular to the palm (dotted arrow). In both these configurations, the thumb is abducted, opposing the fingertips. (c) Non-Prehensile Grasp: the whole hand works as a unit, with a single Virtual Finger. (d) The hand is shaped as a "Hook". The thumb is adducted: its direction follows the palm one.

### *Virtual Fingers*

Iberall defined the *Virtual Finger* as an abstract representation of a combination of fingers applying forces in the same direction, and working as a unit [Iberall, 1997]. For instance, the Index and Middle finger of the Figure 5.5-a or the four long fingers of the Figure 5.5-c constitute a single virtual finger as they apply forces in the same direction.

Grasps are by essence "prehensile", they provide the ability to hold on to things, especially by curling around them. All of the Prehensile grasps count at least two virtual fingers, as fingers do need to be constraining an object from two directions to perform a "clamping" mechanism and enable its manipulation. However, Cutkosky defined a non-prehensile grasp, formed from a single Virtual finger. This grasp hence involves the whole hand, as a unit, and can be used to perform the translation of an object for instance, while pushing or pulling on it [Cutkosky and Howe, 1990] (Figure 5.5-c-d).

The virtual fingers are a key in the understanding of human grasp [Baud-Bovy and Soechting, 2001, Gilster et al., 2012, Iberall, 1987], as they combine both the hand biomechanics and the interactions hand/objects.

### *Grasp Types*

Two main types of grasp are currently depicted in the literature.

### *Precision Grasp (Figure 5.5 - a)*

In a precision grasp (Figure 5.6-b), "the hand is able to perform intrisic movements" [Feix et al., 2016, Cutkosky, 1989, Kamakura et al., 1980, Gonzalez et al., 2013]. This means that the manipulation of the object relies on a few phalanges and the fingers are able to displace an object without involving the arm or wrist displacement. This type of grasp is usually performed through the fingertips, and with decreased object sizes [Cutkosky, 1989].

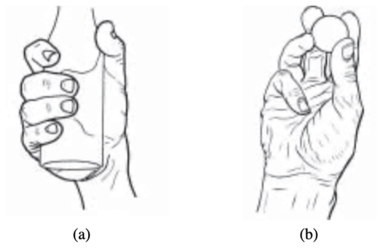



Figure 5.6: Power (a) vs Precision (b) grasps, from [Yokokohji et al., 2005, Kapandji, 1982].

### *Power Grasp - (Figure 5.5 - b)*

On the opposite, a power grasp (Figure 5.6-a) is qualified by "a rigid relationship between the object and the hand" [Feix et al., 2016, Cutkosky, 1989, Kamakura et al., 1980, Gonzalez et al., 2013]. This means that in order to manipulate the object and modify its position/orientation, the entire hand is involved. Gestures then result from the wrist or arm displacements. This type of grasp usually involves the palm, and/or multiple phalanges from a finger, and increased object sizes [Cutkosky, 1989].

### *Opposition Space*

The opposition space corresponds to the direction applied between the hand and the object. There are three types of opposition: pad, palm, and side (Figure 5.7 below).

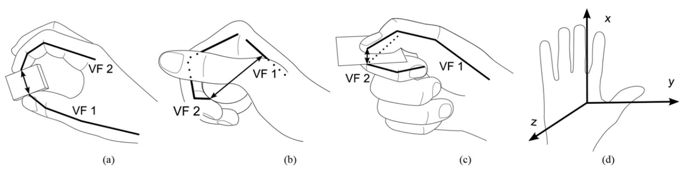



Figure 5.7: Opposition Space from [Feix et al., 2016]: "The abbreviation VF refers to Virtual Finger. (a) Pad Opposition. (b) Palm Opposition. (c) Side Opposition. (d) Hand Coordinate System."

Pad opposition corresponds to a grasp "where hand surfaces are parallel to the palm" (Figure 5.5 -a [Feix et al., 2016], the arrow between the index and thumb is parallel to the dotted arrow representing the palm); Palm opposition's direction is generally perpendicular to the palm (Figure 5.5 - b); Side opposition is in a direction transverse to the palm.

### *Thumb Position*

The last property is the thumb position. It can either be adducted, following the palm direction (see Figure 5.5-c-d), or abducted, able to oppose the fingertips (see Figure 5.5-a-b). An adducted position will for instance allow for a "hook" posture [Kamakura et al., 1980] (Figure 5.5 - d). All of the pad opposition grasps require the thumb to be abducted, to be able to perform the "pinching" of the objects when manipulating them.

> Taxonomies exploit the Virtual Fingers numbers, opposition types and thumb position to determine the type of grasp a user is performing (force, precision) [Feix et al., 2016].

### *Background Analysis*

By analysing the different taxonomies, we defined what we call "grasp features" (see subsequent section). In all of the taxonomies, we noticed that all the grasps involve the thumb and index, and wondered: how to geometrically and quantitatively use this information?

From an object manipulation perspective, we believe that focusing on the vector between the thumb and index respective pads, which norm is often referenced to as "grasp aperture" [Mon-Williams and Tresilian, 2001, Fukui et al., 2006], provides us with a wide set of probabilities for hand/object contact locations (Figure 5.12 - c, Figure 5.8 - d).

Also, what differentiates a power grasp from a precision one when grasping the same object? Can we define a feature quantifying this? We notice that the main difference between a power and a precision grasp, in a geometrical way, is the *depth* of the grasp within the hand. While most precision grasps remain at the fingertips (eg the boundaries of the hand), power grasps involve more phalanges and can hence be considered as more "in-depth" within the hand. On Figure 5.5, we notice the ball is grasped through its depth when a power grasp is performed. Extracting this feature provides information regarding hand/object contact locations: a grasp on an object is only performed within a hand depth (Figure 5.8 - d).

We also want to distinguish whether an object is to be manipulated from its top, its sides or its bottom, and therefore to find a feature quantifying this.

Finally, we can learn from the angle between the thumb, palm and index global directions to define if the grasp is composed from a single Virtual Finger (the formally discussed "non-prehensile" grasp, Figure 5.5 - d, Figure 5.8 - b). This information can potentially be extracted as well.

The next section will use this primal background analysis to define our four key features, as a basis to elaborate our model.

## 5.4 *Feature extraction*

From our previous Background Analysis (Section 5.3), we define 4 key features from the hand geometry.

We define $P_T$, $P_I$, $P_P$, as the respective 3D positions of the thumb pad, index pad and palm center.

### *Feature 1: Opposition Vector - Figure 5.8 - a)*

The index and thumb often are to be considered in a grasp: they usually form two of the "Virtual Fingers" composing a grasp; their orientation inform us of the opposition space. It was demonstrated that the formation of the finger grip occurs during the hand transportation in natural prehension movements [Jeannerod, 1984].

Consequently, we define a vector, called the **"Opposition Vector"**, between these two finger pads ($L$ is its norm).

$$\overrightarrow{Opp} = \overrightarrow{P_T P_I}$$

$$L = \|\overrightarrow{P_T P_I}\|$$

### *Feature 2: Thumb, Index and Palm directions (Figure 5.8 - b)*

The angle from the thumb and palm directions can suggest some types of grasps and manipulations (for instance, pushing or pulling with a whole hand). Whenever they are aligned, but the index one is not, we can suggest that a "hook" grasp is likely to be performed (Figure 5.5 - d). These features would for instance suggest that a *single "large" contact*, grouping the whole finger pad and the palm will occur. As the hand is sensible to edges for instance, it is important to dissociate the width of the future manipulated area.
Another information we can extract from it is that the grasp might be **bi-manual**.

Indeed, if the hand only possesses a single Virtual Finger, in order to be "securely held"[2] for a task different than "pushing" or "pulling", this suggests that both hands are going to be used for manipulation.

[2] From the Grasp definition [Feix et al., 2016].

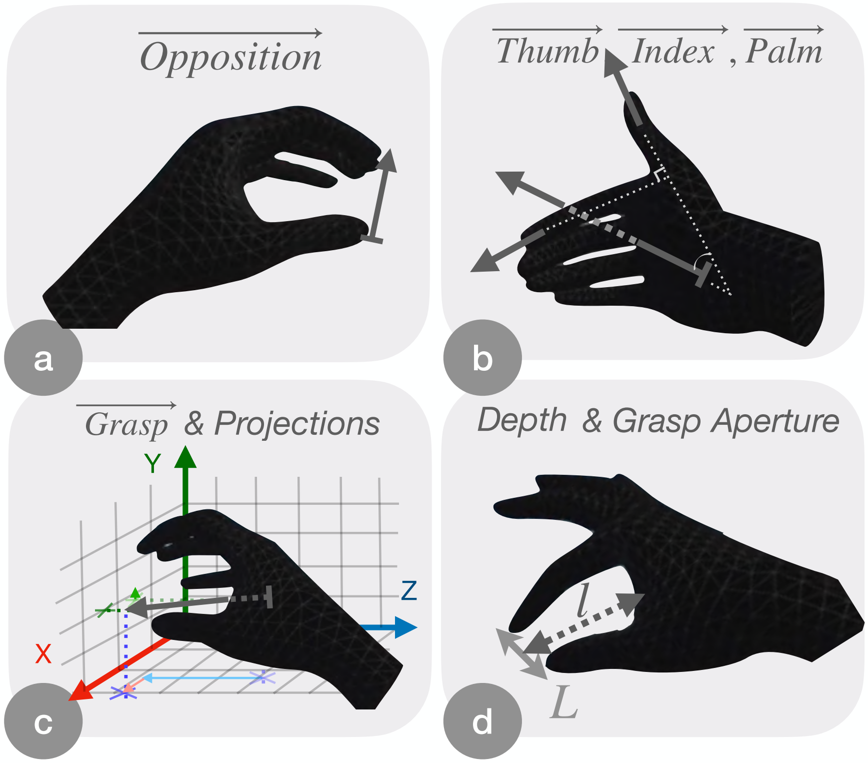



Figure 5.8: Features extracted from users' hands: (a) The "opposition vector". It links the thumb pad to the index one. (b) The thumb, index, and palm directions: we here can note the palm and thumb are following the same directions, with a small angle separating them, while the thumb and index directions are perpendicular. (c) We extract the palm orientation and project it over the coordinate system to define the Grasp direction. Here, the upward component is significantly smaller than the other ones: the grasp will be performed from the sides. (d) The "depth" and "grasp aperture" distances. We depict the grasp aperture L, being the "opposition vector" norm, and the grasp depth l, being the distance between the grasp aperture midpoint and the palm center.

*Feature 3: Palm & Grasp Direction (Figure 5.8 - c)*

We also need a feature to define whether a grasp is performed from the top or the side of an object. This decision is often made very soon in the gesture leading to the grasp. We define the palm direction as the palm center's trajectory[3]:

[3] t represents the time

$$\overrightarrow{Grasp} = \overrightarrow{P_{P,t}P_{P,t-1}}$$

By projecting this vector over the XYZ coordinate system, we can define the future **grasp direction** along with its greater component: on Figure 5.8 - c, the greater component is the $Z$ one: the grasp will be performed from the object's side, along the $\overrightarrow{Z}$ direction.

*Feature 4: Grasp Depth (Figure 5.8 - d)*

Geometrically, a grasp always occurs within the aperture between the Opposition vector and the palm. Even if a hand were to be non-folded (eg non-prehensile grasp), this remains valid as the contact would be colinear to the Opposition vector.

Also, as the grasp aperture and finger grip are formed during the movement [Jeannerod, 1984], we deducted that the object "in-depth" contact point should be extracted at an early stage of the grasp. We thus introduce the grasp depth $l$:

$$\vec{l} = \overrightarrow{P_p P_m}$$

where $P_m$ is the midpoint of the grasp aperture:

$$P_m = \frac{P_T + P_I}{2}$$

## 5.5 Model Implementation

We now present our computational model, which predicts the future contact points within the virtual object of interest. It relies on the four mathematical features elaborated from grasp taxonomies. The general approach is summarized in the illustrated pipeline **Figure 5.12**.

### 5.5.1 General approach

Our previous features are hand geometry-based. We hence decided to explore this perspective more thoroughly, and to create a geometric tool to leverage their use. We decided to create planes, acting as **cut sections** over the objects of interest.

### 5.5.2 Inputs

The inputs are 3D representations (positions and orientations) of the hand palm, index, thumb; and the object of interest $OOI$. We use the Oculus Quest hands to extract the users whole hands.

### 5.5.3 Plane Generation

We first define $C_{OOI}$ as the Closest point from the Object of interest (OOI) to the grasp aperture midpoint $P_m$ (see Section 5.4).

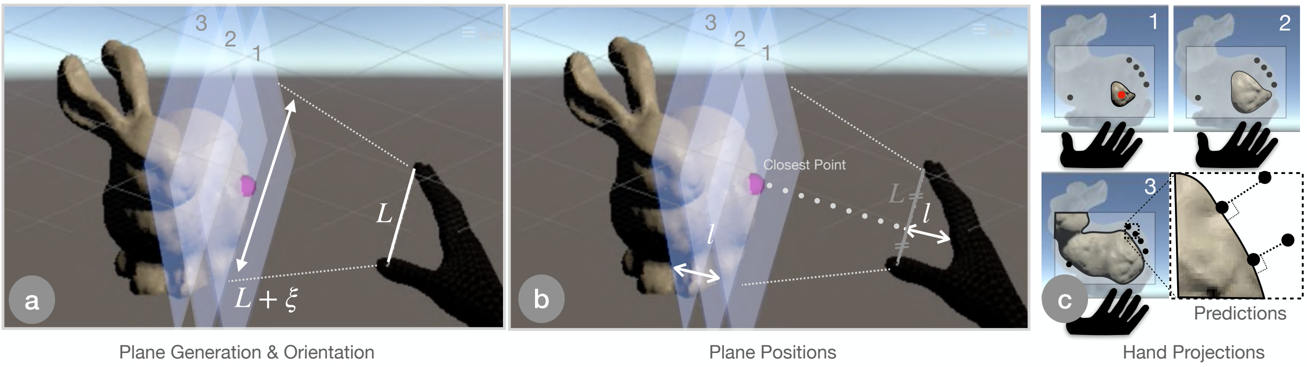



Figure 5.9: (a) Plane Generation: The Cut sections (1,2,3) lengths are an extension of the Grasp Aperture $L$. They are parallel to it. (b) Plane Positions: They are located from the Grasp aperture mid-point's closest point over the object of interest (pink sphere) and spread over a Grasp Depth length $l$. (c) Hand Projections: Each plane cuts the object of interest. The hand phalanges are projected onto each of them (1, 2, 3). The spheres represent the hand projections: they are the hand phalanges projections on the cut sections. *Predictions*: The hand projections are projected onto the intersection between the Object of interest and the Cut Sections.

### *Orienting the Planes*

To define the cut sections global orientation, we extract the palm direction. We project it over the XYZ coordinate system, and find its greatest component (over X, Y, or Z) (see Figure 5.8 - c, Figure 5.10) (see Algorithm 1).

This defines whether the plane generation should be *horizontal* or *vertical*. This gives us our first plane directing vector.

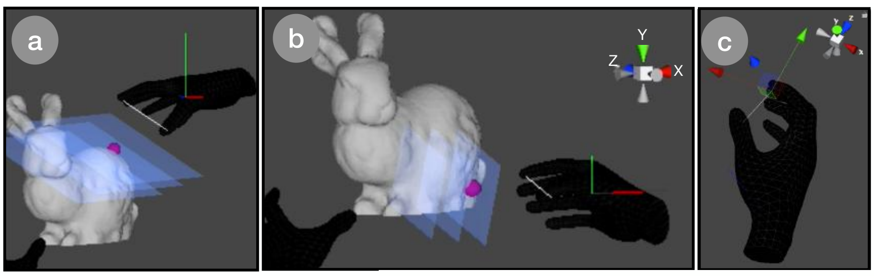
The cut sections are then rotated to be **colinear** to the Opposition vector (see Figure 5.10, which is the plane second directing vector (see Figure 5.8 - a). The plane normal $\overrightarrow{n}$ is therefore defined by the cross product of these two directing vectors.

When the palm information is not available to extract, for instance if only two trackers (on the thumb and index) are being used in a VR environment, we can trade the palm orientation for the following:

$$\overrightarrow{Palm} \approx \overrightarrow{P_T P_I} \wedge \overrightarrow{\theta_{z,I}}$$

where $\overrightarrow{\theta_{z,I}}$ is the index' local $\overrightarrow{Z}$ vector (see Figure 5.10 - c).

Figure 5.10: The same Opposition Vector is involved in these two gestures. The Palm direction is here projected over the XYZ coordinate system, and their respective component are displayed according to Unity coloring system (X = red, Y = green, Z = blue). The planes are parallel to the Opposition Vector (displayed in white). (a) The Y component is greater than the other ones, the grasp will be performed from the top. (b) The X component is greater than the other two: the grasp will be performed from the X side. The planes are cutting the object along this direction. (c) The index local referential and the opposition vector (white).



**Algorithm 1** Orienting the Cut Sections; The inputs are the palm direction $\overrightarrow{Palm}$ and the opposition vector $\overrightarrow{Opp}$. We define the cut sections normal vector $\overrightarrow{n}$.

**procedure** ORIENTATION PLANE ($\overrightarrow{Palm}$,$\overrightarrow{Opp}$) ▷ Defining two non colinear directing vectors and the plane normal $\overrightarrow{n}$.
  **if** $proj_{\mathbf{y}}\overrightarrow{Palm} > proj_{\mathbf{x,z}}\overrightarrow{Palm}$ **then**
    $\overrightarrow{d_1} \leftarrow (0, 0, 1)$ ▷ Plane is Horizontal
  **else**
    $\overrightarrow{d_1} \leftarrow (0, 1, 0)$ ▷ Plane is Vertical
  **end if**
  $\overrightarrow{n} \leftarrow \overrightarrow{d_1} \wedge \overrightarrow{Opp}$ ▷ Plane normal
**end procedure**

### *Positioning the Planes*

The first plane's origin is located at $C_{OOI}$ (pink sphere in Figure 5.9). We spread two other planes over the Grasp Depth length $l$ (total number of planes $k = 3$). $C_{OOI}$ is defined to be dependent on the Object of interest's closest point from $P_m$. To keep the "depth" property even when the user's hands are getting closer to the object, we inverse the direction of the spread in this configuration (see Algorithm 2).

We define the plane $i$ position $P_{plane,i}$ in Algorithm 2. The cut sections lengths (in their virtual representation) are an extension of the grasp aperture.

**Algorithm 2** Positioning the Cut Section $i$ among the $k$ ones. The inputs are: $P_m$, midpoint of the grasp aperture; $\overrightarrow{l}$, grasp depth (norm = $l$); $C_{OOI}$ the closest point from the Object of interest to $P_m$.

**procedure** POSITION PLANE $i$, ($\overrightarrow{l}$, $C_{OOI}$, $k$, $P_m$)
  **if** $P_m - C_{OOI} > l$ **then**
    ▷ Predict within the object's depth
    $P_{plane,i} \leftarrow C_{OOI} - \overrightarrow{l} * \frac{i}{(k-1)}$
  **else** ▷ Keep the Depth Predictions when Grasping
    $P_{plane,i} \leftarrow C_{OOI} + \overrightarrow{l} * \frac{i}{(k-1)}$
  **end if**
  **return** $P_{plane,i}$ ▷ Position of the Plane #$i$
**end procedure**

### *Projection of the Hand onto the Cut Sections*

Once the planes are oriented and positioned correctly, we project the hand phalanges onto each of them (see Figure 5.9 - c). We define this projection as $Proj_{k,phalanx}$.

We also project them at the intersection between the object of interest and the cut sections $Proj_{OOI,k,phalanx}$.

### 5.5.4 Output: Predictions of Future Contact Points

We compare the distances from each phalanx projection among the three planes (see Figure 5.9 - Projections). For each cut section $k$, we compare the distances between $Proj_{k,phalanx}$ and $Proj_{OOI,k,phalanx}$. The final phalanx prediction is $Proj_{OOI,k,phalanx}$ with the smallest distance. This projection gives the position of the future contact points (Figure 5.11). We can also extract its local shape, and its different substance-related properties [Lederman and Klatzky, 1987].

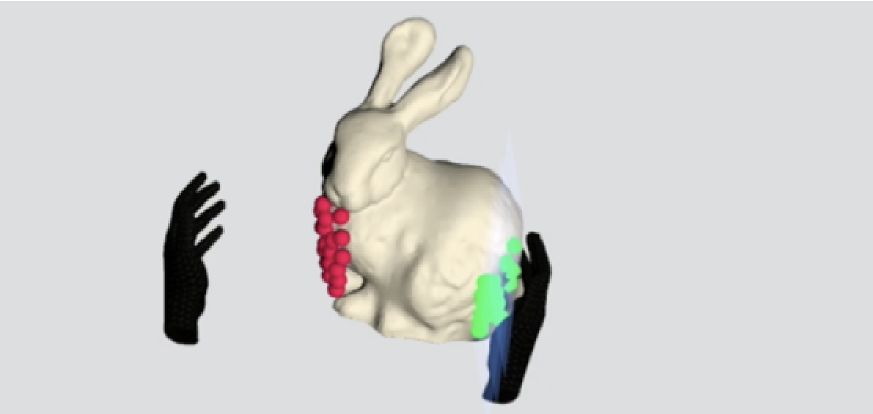


Figure 5.11: Predictions: Future contact positions. Red circles: Left hand predictions; Green circles: Right hand predictions.

## 5.6 Model Properties

This model shows multiple benefits. First, it is user-independent. Indeed, the hand geometry and its dynamism while grasping does not change among users. This is a direct consequence of using taxonomies: it is adapted to any grasp and any user. Second, it can be used as a real-time model for predicting grasp intentions locations in VR. Third, it is adapted for both hands, and for bi-manual interactions. Fourth, as the contact point is predicted, the zone of interest shape can also be deducted quite easily by extracting the future contact point primitive.

As it was depicted in Chapter 4, Robotic Graphics interface scenarios have 3 steps: intentions, displacement, interaction. The information from the model are intention-related. This provides the interface with a future contact location *and* the associated local haptic properties of the virtual object. The interface can displace itself to this location, and display or simulate the adequate sub-object.

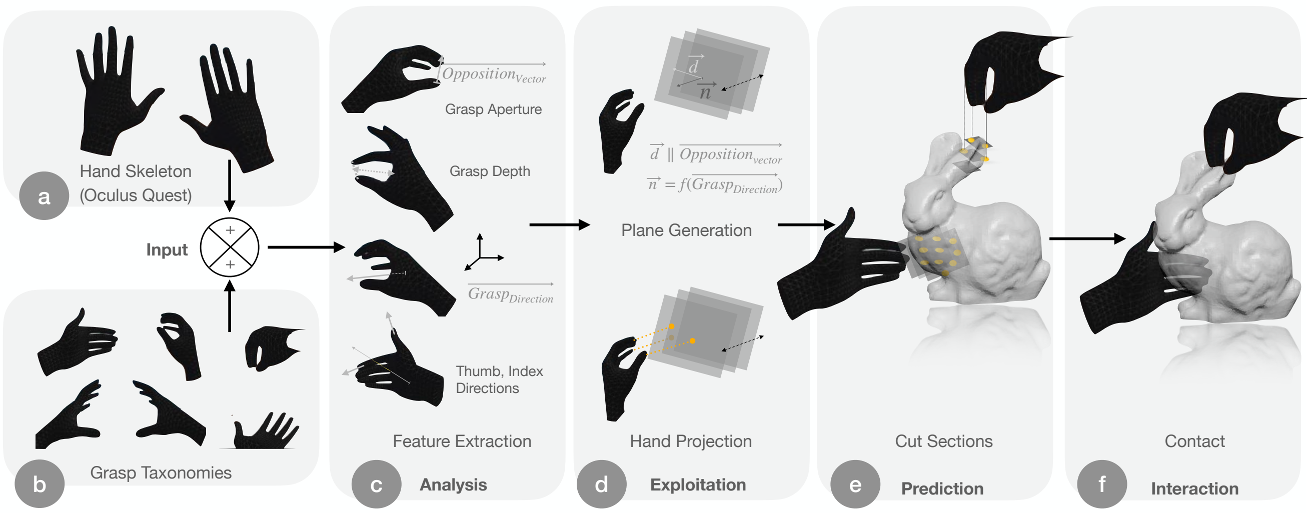



Figure 5.12: We present a novel User Grasp Intention Prediction model for Bare-hands interactions in VR (eg manipulation tasks). Based on the (a) users' skeleton, extracted from the Oculus Quest, and (b) Grasp taxonomies, (c) we analyze and extract 4 geometric features to anticipate the users' grasp behaviour. (d) We exploit these features to generate planes, on which the users' skeletons is projected. These planes normals are a function of the users' *Grasp Direction*, their direction vector is colinear to the *Opposition Vector*, and their global spacing matches the users' *Grasp Depth*. (e) These planes create Cut Sections over a virtual object of interest, and predict the users' future contact locations, prior to performing a bare-hand interaction. (f) The user interacts with the object of interest at the predicted positions.

> We will evaluate our model accuracy prior to contact in the next section. Note that the model does not predict the number of future contact points: **if a contact is to occur, the model predicts its future absolute position**. The model does not discriminate the grasp type to analyse the number of future contact points.

## 5.7 Evaluation

We conducted a user study to test the capacity of our model to accurately predict the user's grasp positions when performing different manipulations (e.g. hold, push, pull) on various objects (e.g. cube, cylinder). More precisely, we estimate the distance between the actual and predicted touch contacts at different times prior to the interactions.

### 5.7.1 Participants and Apparatus

#### *Participants*

We recruited 7 participants from our acquaintances and laboratory (3 female), aged from 25 to 37 (mean = 30, std = 4). Five users were familiar with VR technologies, 2 of them were experiencing VR for the first time, and none of the users had ever used a head-mounted display (HMD) without controllers. No rewards were attributed to the participants. All the users were right-handed.

### *Apparatus*

The participants wore an Oculus Quest HMD without any supplementary sensors, controllers nor wearable devices. They adjusted their HMD to their convenience, and remained in a standing position during the whole experiment.

The 3D scene was designed on Unity3D, and compiled as an Android application. The scene contained the avatar hands (e.g. Figure 5.13) available on the Oculus Quest as well as the virtual object to manipulate (white) and its target location (red) as shown on Figure 5.14. Walls were surrounding the scene, and users were standing in front of a virtual table. The virtual objects were not subject to Unity3D's physics engine (gravity) and were attached to the hands[4] when a collision occurred, to move accordingly with them.

[4] More specifically, the objects were attached to $P_m$ to enable a smooth manipulation.

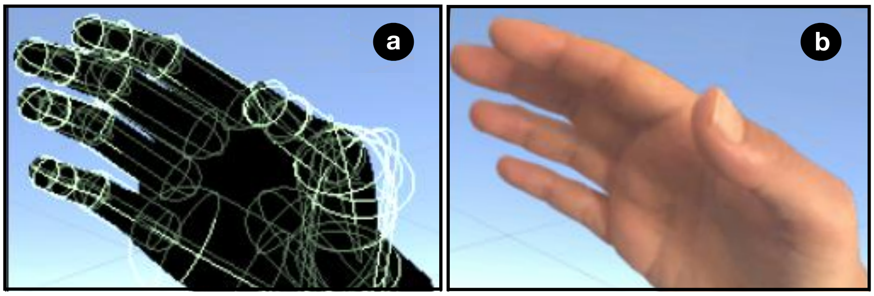



Figure 5.13: Hand Representations: (a) Virtual hand, with associated Phalanges (in green); (b) Real hand during the game: the user does not wear any tracker nor holds a controller.

## 5.7.2 *Method*

### *Conditions*

We controlled two factors related to the objects (SIZE and SHAPE) as well as one factor related to the task MANIPULATION, as the nature of the grasp is object/task-dependent.

The three object SIZES were 5cm, 10cm and 25cm. These sizes were chosen to be relatively small, medium or large compared to an average hand size ($\approx$ 18cm).

We considered nine object SHAPES. Two shapes were simple: Cube and Cylinder (Figure 5.14 - a,b). Seven shapes, corresponding to the seven first digits, were more complex {0, 1, 2, 3, 4, 5, 6}. The complex shape objects are combinations of simple primitives with different radii, or sharp/round angles. They offer more grasp opportunities. For instance, the digit 1 can be grasped by its rectangle base or its cylinder trunk or from its spherical top (see Figure 5.14).

Finally, we considered five MANIPULATIONS – "Hold, Pull, Push, Raise and Push down" – (Figure 5.14) involving different grasp types, opposition space and thumb position (see Section 5.3), and representing the common real world day-to-day manipulations.

### *Task*

The instruction was displayed on the virtual wall and indicated the manipulation to perform (e.g. hold, push) to place the white object into the red target location (see Figure 5.14). Once the object was positioned in the target location, this latter became green.

As we are interested in the grasp intentions *prior* to contact, the virtual objects disappeared 3 seconds once the grasp was performed (ie when a contact between the object and any hand phalanx was maintained) - even if the user was not finished moving it to accomplish the given MANIPULATION.

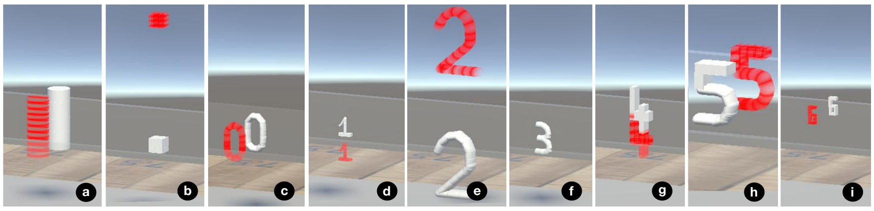


Figure 5.14: The task consists of placing the white virtual object with various shape and size into the red phantom target location with a given manipulation (e.g. hold, push, pull): (a) Medium Cylinder to be pulled; (b) Small Cube to be raised; (c) Medium 0 to be pulled; (d) Small 1 to be pushed down; (e) Large 2 to be raised; (f) Small 3 to be simply touched; (g) Medium 4 to be pushed down; (h) Large 5 to be pushed; (i) Small 6 to be pulled.

### *Procedure*

Participants were first asked to fill in a consent form, validated by the university Ethics Committee. They were informed about the experience, its goal and duration.

During the experiment, they were also asked to interact as naturally as possible. In particular, they were free to use one or two hands and the desired number of fingers. The participants HMD view was cast over the experimenter's phone, for her to overview the experiment's progress and ensure the task was well understood. The duration of the experiment was approximately 20 minutes per participant (mean = 21, std = 1.2mn). No participant felt any discomfort during the experiment.

### *Design*

We used a within-participant design. Each participant tested the 135 conditions, corresponding to 5 MANIPULATION $\times$ 9 SHAPE $\times$ 3 SIZE in a random order. The total number of trials is 7 participants $\times$ 135 conditions = 945 trials.

*Measures*

We collected each of Oculus avatar hands' phalanges name, position, orientation and created their associated colliders[5] (see Figure 5.13). The position and orientation of the Oculus Quest HMD was also recorded. We recorded each configuration number, and each objects' of interest position and orientation. We collected all the data at a 60 fps frame rate.

[5] We kept the initial properties of the colliders proposed by Oculus, however they often lost tracking and were not following the users' skeleton accurately. We associated our colliders to skeleton positions, which worked well and allowed various interactions.

### 5.7.3 Results

*Reach-to-Grasp Duration.* When a reach-to-grasp duration was above 4s, either (a) the tracking was lost and the user had to wait to get their virtual hands back, or (b) the users were exploring the environment. In the following results, we hence summarize the data over a 4s scale and truncate above it. Indeed, the data above it do not represent our samples (small amount of data) and do no show any interest. The reach-to-grasp duration was consistent, as the global standard deviation over the experiment duration was below 1.5 minutes. More than 80% of the grasps were performed under 4s (mean = 3.2s, std = 1.6s).

*Analysis Procedure.* When a contact occurred between the virtual hands and the virtual objects, we recorded it as the contact point, at $t_0$. We then analysed the distance between this contact point and (a) the mean prediction position and (b) the real phalanx position, from $t = -4s$ up to $t_0$, over all users and configurations. We first cleaned our data from the lost tracking, and verified that the grasps were maintained for at least 5 frames. This resulted in a total of 934 grasps to analyse.

Table 5.1: Distances from the predictions to the contact point VS Real phalanx distances to the contact point. The index/thumb data belong to the users right hands (all users were right-handed). As a side note, the sample sizes can be different: the thumb and index pads are not necessarily involved in all the configurations.

| mean (std) | **Predictions** | | | | **Real Positions** | | | |
|---|---|---|---|---|---|---|---|---|
| in mm | All Hand Phalanges | R-Index | R-Thumb | R-Index + R-Thumb | All Hands Phalanges | R-Index | R-Thumb | R-Index + R-Thumb |
| **t = 0** | 3.7 (2.0) | 2.6 (3.2) | 2.6 (2.6) | 2.6 (2.8) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| **t = 0.25s** | 8.7 (3.8) | 6.4 (5.3) | 5.9 (5.1) | 6.1 (5.1) | 10.5 (2.9) | 10.1 (4.9) | 8.6 (3.8) | 9.4 (4.3) |
| **t = 0.5s** | 17.0 (10.3) | 11.2 (7.4) | 9.7 (6.5) | 10.5 (6.8) | 20.8 (12.0) | 20.6 (8.8) | 17.7 (7.8) | 19.1 (8.2) |
| **t = 1.0s** | 30.2 (15.9) | 21.0 (9.4) | 17.7 (9.0) | 19.3 (9.0) | 41.6 (21.3) | 44.7 (17.6) | 38.9 (14.9) | 41.8 (15.8) |
| **t = 2.0s** | 47.6 (18.2) | 35.6 (10.5) | 31.2 (10.9) | 33.7 (10.5) | 71.2 (27.5) | 81.3 (28.1) | 70.6 (24.5) | 76.0 (25.7) |
| **t = 3.0s** | 57.7 (17.8) | 44.3 (11.6) | 41.7 (10.4) | 43.0 (10.2) | 89.4 (28.6) | 102.4 (31.7) | 90.0 (25.9) | 96.2 (28.3) |
| **t = 4.0s** | 64.3 (16.0) | 49.8 (10.8) | 47.8 (7.8) | 48.8 (8.2) | 101.2 (26.0) | 121.8 (36.8) | 106.6 (27.0) | 114.2 (31.3) |

### *Global Results*

We ran simulations using the users data and analysed the distance between the contact points and our predictions prior to interaction. We define the accuracy of the model as the distance between the future contact point and the prediction. It is presented in the Table 5.1. Because all of our participants were right-handed, we also display the results for the users' right thumb/index pads.

The prediction slope is drastically lower than the real phalanges ones: the predictions are indeed always within the vicinity of the future contact points. To validate this, we can notice that the 95-confidence interval of the real positions only meets the Predictions one around 200 ms prior to contact.

We discuss ways to improve these results in Section 5.7.4.

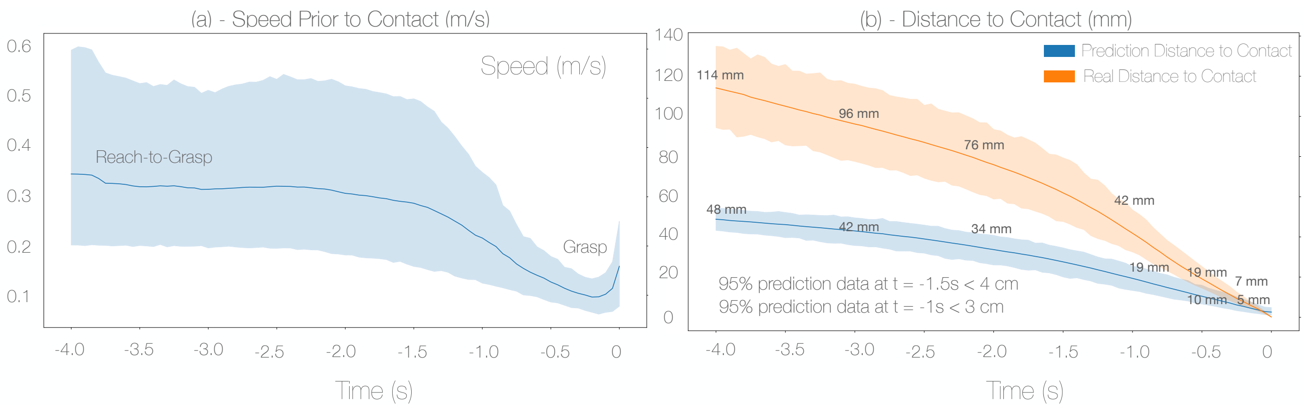



Figure 5.15: Right Index and Thumb Prediction and Real Phalanges (a) speeds (in m/s) and (b) distances to the contact point (in mm). As long as the user is indecisive, the model cannot predict the contact location, as it relies on the users' hands dynamics. Yet, it remains in the contact point vicinity. Intervals show 95-CI.

### *Analysis per Scale*

Ninety-five percent of the prediction data is below 3cm and 4cm of the final contact point at respectively 1s and 1.5s, prior to interaction, which indicates that our model can at least predict the contact point vicinity prior to interaction with a good accuracy.

In Figure 5.16, both of the hands data (19 phalanges per hand) are used in this figure, as users were most often using both of their hands to interact with large objects (see Section 5.7.3). We show the relation between the distances to the contact points and the objects' scales. We notice that large objects show the best accuracy prior to contact.

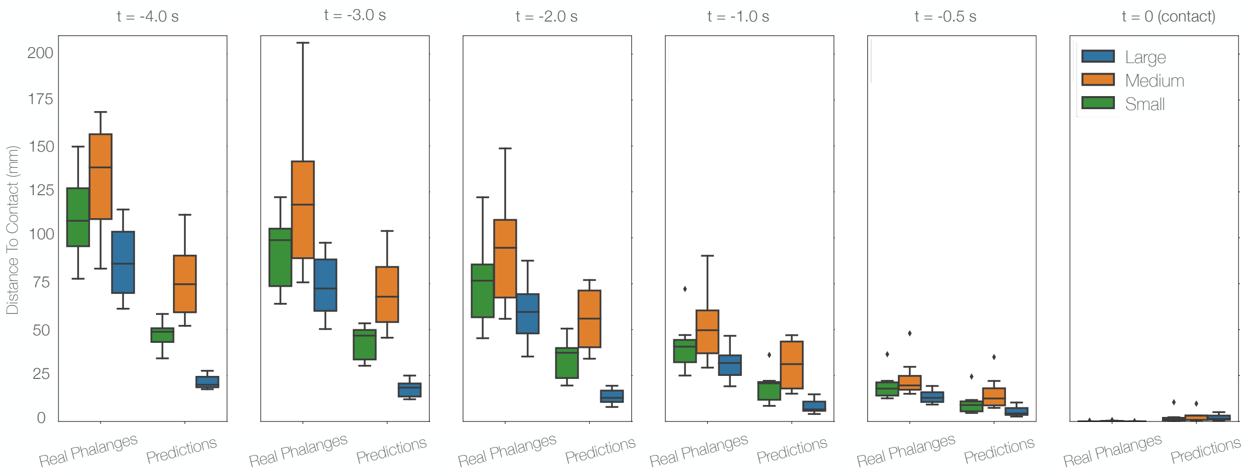



Figure 5.16: All the phalanges (both hands) Predictions/Real positions distances to the contact points, as a function of the objects' sizes, at $t_0$,$t_{25\%}$,$t_{50\%}$,$t_{75\%}$,$t_{100\%}$. We note that the predictions remain at all time in the vicinity of the future contact points.

### *Analysis per Manipulation*

The tasks also had an impact on our model accuracy. Indeed, we note in Figure 5.17 that the "Raise" prediction to contact distance is drastically higher than the other ones. As the users were placing their hands below the objects to raise them, we believe the hand projections could not reach the right contact points from the beginning. In a scenario where the users would be free to perform any gesture, we do believe that using more information from the hand (grasp direction for instance), we could predict a contact over these areas at an early stage (see Section 5.7.4).

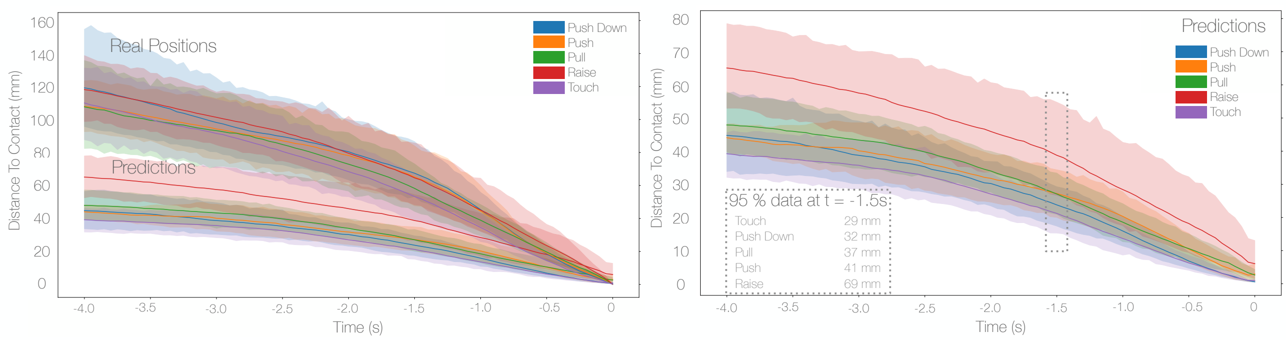



Figure 5.17: Right Index and Thumb predictions/real positions distances to the contact point, as a function of time prior to contact and performed manipulation gesture. Intervals show 95-CI.

### *Qualitative Feedback*

Our experiment confirms that interacting with a simple avatar hand and bare-hands interactions is **fun** and **"natural"** [Weise et al., 2020]. P1 and P6 reported that it was fun to be allowed to perform any types of interactions with the objects. They took advantage of the freedom that was given to them to grasp objects in many various and unexpected ways (Figure 5.18). For instance, P1 interacted with the large cube (Figure 5.18- a) by pushing it with his fists. Similarly, P6 experienced holding objects through two of her fingertips (Figure 5.18 - c,d); and was satisfied to be able to literally move the objects with these unexpected types of grasps. All participants interacted with both of their hands to manipulate large objects, notably the big cube (Figure 5.18 - b). Five participants instinctively spoke up during the experiments, globally reporting that "they knew it was silly to hold big objects with two hands, but they felt they were heavier and had to manipulate them with both of their hands and through their geometries". Users had a tendency of considering lots of different grasps with medium sized objects, and changed their grasp configurations during the same grasp trial. We believe that unencumbered bare-hands interactions enable a **large variety of movements**.

> These behaviours actually suggest that our motivations are valid and that unencumbered bare-hands interactions enable a arge variety of movements. Grasping in VR through objects' affordances and in a "natural" way is important for immersive experiences. We noticed a strong **correlation** between the **objects**' sizes, shapes, the **manipulation** tasks, and the **users hand configurations** and grasps. We discuss how to take advantage of it to improve our model detection time in Section 5.7.4.

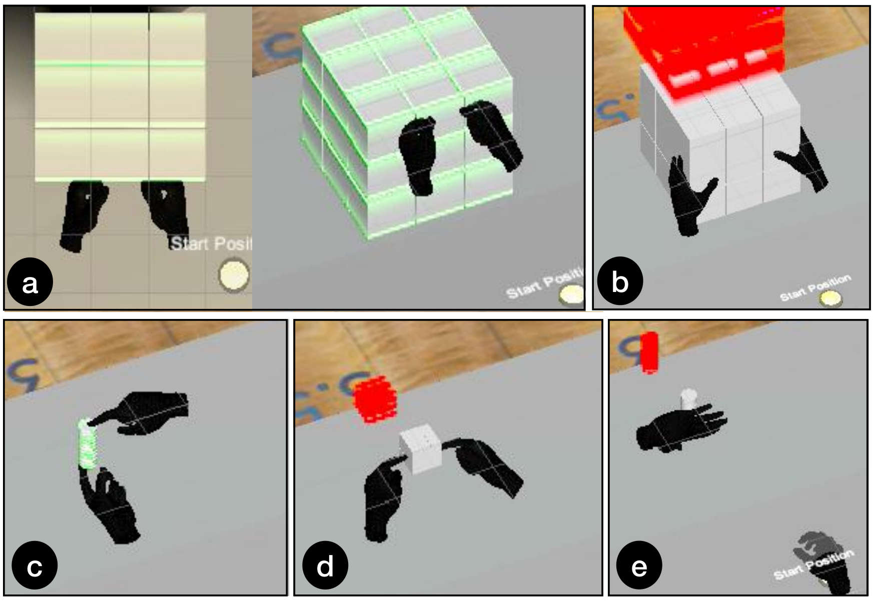



Figure 5.18: Unexpected Grasps from our Data collection: (a) a user decided to push the cube using its fists; (b) All users used at least once both their hands to manipulate the big cube, here while raising it; (c) P6 locked the small cylinder position by holding it between two fingertips; (d) Same thing happened with the small cube, being moved over with two single fingers; (e) A user pushed the small cylinder with an upside-down hand. All of these users reported they had fun moving the objects as they wished.

### 5.7.4 *Discussion*

In this subsection, we summarise our main findings, provide directions to extend the model and discuss another usage of the model (hardware specifications).

### Main Findings

Qualitatively, we show that users appreciate the opportunity to perform any types of grasps, and take advantage of bare-hands interactions to manipulate virtual objects in a natural manner, much as with real-life interactions. Quantitatively, the results are promising as our model identifies the future contact points vicinity early during the reach-to-grasp phase, and provides a refined location (accuracy below < 3cm) more than a second prior to interaction. It also shows to be working with no regards to the users' grasp configurations, the manipulated objects or the manipulation tasks, even involving both of the users hands (two-handed interactions).

### Extending the Model

As future work, we see four main directions to extend our user-intention model.

*Further Validation of the Model* Our user experience could benefit from being tested with more participants, in particular including left-handed users. We could also test our model with more common objects of various primitives and with tasks beyond the ones previously proposed.

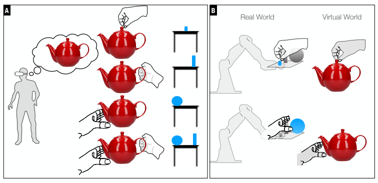



Figure 5.19: A. A user wants to interact with a teapot: a complex shaped object - primitives are different *within* the object. Depending on his manipulation, the user will not interact with the same primitive; it can be single or two-handed, from the top or from the sides. B. As an example of our model use-cases, a robotic arm displays the correct object primitive to represent a teapot in the virtual environment.

*Using Semantic Information* Using some semantic information about the object or the task can be used as *priors* to refine the predictions of the model both in terms of time and accuracy. Indeed, the environments constrain the available users interactions, therefore allowing the designers to add "prior probabilities" over the different object areas. For instance, if we consider the teapot of Figure 5.19, three main areas of interest are more likely to be interacted with: its base, its handle and its top. Moreover, the base is more likely to be interacted with the non-dominant hand while the handle is more likely to be interacted with the dominant one. Similarly, if an object is placed over a desktop, the probability for its bottom to be touched would be null, as this area will be unavailable for direct contact. Prior probabilities can therefore be added accordingly to refine the predictions.

*Using Grasp types* Another promising direction is to extend our model to return the grasp type and refine the predictions. The type of grasps can be determined from our (or additional) mathematical features or by using a Machine Learning algorithm. This information can potentially provide the future number of contact points, for a multi-fingered tangible interface to either display this exact number of physical contact points (such as in [Shigeta et al., 2007]) or for a redirection to be applied *per finger*.

### *Hardware Specifications*

We currently used our user-intention model to predict the future contact points as soon as possible so that the given system can adapt accordingly in *real time*. However, we can also used our model the other way around. Indeed, our empirical results suggest that for a given precision (eg 3cm), a correct prediction can be made *t* seconds (respectively 1s) before the contacts occur. This information can be useful, *offline*, in the early stage of the design of the system to help the designers define the hardware specifications, ie. motor speed, maximum distance between/to the physical props, etc.

## *5.8 Conclusion*

This model has been elaborated based on a thorough analysis of grasp taxonomies and reach-to-grasp behaviours, which resulted in the creation of four geometrical key features. These are used to create geometrical tools (planes), acting as cut sections over the objects of interest in VR. This model is addressed to VR and Haptics designers: we believe that coupling haptic interfaces with our model can enhance bare-hands interactions, such as exploration, manipulation (modifying the object position/orientation), or even edition (modifying the object structure). Anticipating the users grasp intentions provides valuable information for interfaces/interaction techniques design and control. We conducted a user study which qualitatively showed that users perform "natural" interactions in VR even when not requested to (eg holding the large-scale objects with both hands), and quantitatively showed a reasonable accuracy for our model with an acceptable prediction time. We finally provided solutions to improve these results. This model acquires the absolute future positions of contact for fine hands interactions, despite only working with **single** objects of interest. It can be used for any type of Robotic Graphics, as suggested in Figure 5.2.

In the next chapter, we will focus on the *design* of CoVR as a Robotic Graphics **interface**, in non-deterministic scenarios involving **multiple** objects of interest. A between-objects model will therefore be implemented as a complement to this current within-object model, and tweaked with the CoVR's mechanical specifications, such as Section 5.7.4 suggests it. This chapter will define CoVR's mechanical and hardware requirements based on the features evoked in our Analytical Framework (Part I). Finally, the last chapter on this current part (Part II) will cater for CoVR's interaction opportunities and its evaluation from a *user* perspective.

WHAT YOU MUST REMEMBER

*Positioning:*

- Grasping is task and object dependent.
- A bare-hands interaction such as grasp, manipulation, edition, requires more information than a simple target acquisition task; as they usually involve different depths, surfaces and shape primitives.

*Contributions:*

- A model predicting bare-hands interactions in VR prior to contact, and its evaluation.
- The model is destined to Haptics and VR designers: it provides shape and location information from the future contact points *prior to interaction*.
- A replicable and usable *Software brick* for Robotic Graphics interfaces and more globally, for providing Haptics in VR.

6

# Robotised Interface Design and Between-Objects User Intention Prediction Model

CoVR was introduced as a Robotised Tangible interface, anticipating the users' intentions to encounter them with the appropriate feedback. I previously defined how to anticipate the users' absolute future contact points over a single object of interest. In this chapter, I focus on enabling **non-deterministic scenarios** - ie I focus on designing a Between-Objects User Intention Prediction model. This comes as to complement Chapter 5 in the first step of our Robotic Graphics scenario (Chapter 4): *Intentions* (Figure 6.1).

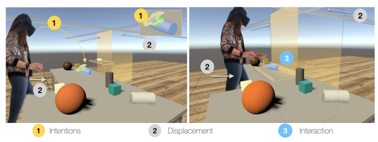


Figure 6.1: Reminder of a classic Robotic Graphics scenario, from Chapter 4.

This Between-Objects intention prediction part of our *Intention* scenario step is yet intrinsically linked to the *Displacement* scenario step (Figure 6.1). Indeed, the *intention algorithm* delay depends on the number of available objects, the spacing between them, their sizes (Chapter 4, Section 4.3.1). Similarly, the *displacement*

*of a Robotic Graphics* interface can also be altered by these parameters (longer distance to travel etc).
In the design of a Robotic Graphics interface in non-deterministic scenarios, the between-objects intention prediction model is dependent on the interface's displacement capabilities: it is required to provide a sufficient delay based on the interface mechanical capabilities (such as speed and accuracy). Reciprocally, the interface's specifications should also be designed with respect to the algorithm delay.

In this chapter, I therefore choose to combine **CoVR's between-objects user intention prediction model** (Step #1) with **CoVR's hardware design** (Step #2). The final chapter (Chapter 7) in this part (Part II) will cover the Step #3 of our Robotic Graphics scenario: *Interaction*.

This chapter focuses on the design of CoVR, and simultenaously aims to cover our global research questions:

HAPTIC INTERACTION TECHNIQUES *How to enable intuitive interaction techniques?*

HAPTIC FEEDBACK *How to provide users with both fine tactile and large kinesthetic feedback?*

HAPTIC SOLUTION *What are the hardware requirements for such an interface?*

## *6.1 Approach*

The approach promoted in this chapter is to convert Haptic Interaction techniques and Haptic feedback requirements from Part I into mechanical specifications to define our Haptic Solution.

*In terms of Haptic interaction techniques*, we promote unencumbered bare-hands interactions. We do not want to add any more contraption to the user. The previous chapter demonstrated *how to anticipate the users interactions **within** an object of interest* when a single object was available; in this chapter, we focus on a complementary question: *how to anticipate **which** object of interest the users are about to interact with* when multiple objects are available?

*In terms of Haptic Feedback*, the interface should be able to provide both hand-scale haptic feedback (for instance by displaying objects to the users) and large kinesthetic feedback (for instance users should be able to push on the virtual world's walls). In these regards, we demonstrated in Chapter 3 that the use of real objects for exploration and manipulation for hand-scale haptic feedback might be sufficient, and in Chapter 4 that large kinesthetic feedback and perceived stiffness can be transposed in robustness specifications. More generally, the interface should enable to explore the virtual world's constrains, such as exploring a wall or pushing on it.

*Haptic Solution*-wise, we lean towards the design of a Robotic Shape Display [McNeely, 1993][1], which specifications are, according to our Analytical Framework (Part I) and Table 6.1:

[1] Robotic Shape Displays are Encountered-Type of Haptic Devices exploiting *real objects*.

*Interactions* – various interaction opportunities with a large workspace,

*Physicality* – the use of passive haptics,

*Modularity* – the use of various props prepared prior to use,

– a replicable and modular interface with the lesser complexity for deployment and use-cases purposes,

– a robust intention algorithm, enabling the interface to anticipate the users next interactions in non-deterministic scenarios,

*Actuation* – a high robustness, to resist to body-scaled user actions, have a high perceived stiffness and enable large embedded masses,

– a high accuracy, for objects to be displayed at the expected locations,

– a sufficient speed to overlay objects of interest prior to interactions,

– a safe interface, moving around the users without any unexpected collision,

– an intuitive use.

| Interaction Opportunities | | | | | | Physicality | Modularity | | | | Actuation & Robotics | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Navigation Workspace | Haptic Features | Exploration | Manipulation | Edition | Whole-Body Involvement | Passive Haptics | Number of Props | Operator | Non-Deterministic Scenarios | Deployment Use-cases | Robustness | Accuracy Speed | Safety | Ease-of-Use |

Table 6.1: Criteria for Analysing Robotic Graphics interfaces, from Chapter 3.

## 6.2 *Concept*

CoVR's concept aims to let the users unencumbered from any contraption: users have their hands free to directly interact with physical objects, hence tutorial on different contraptions is not required. Except for a head mounted display, CoVR does not require instrumenting the users with mechanical contraptions nor sensors, which can be heavy and/or time consuming to setup. It aims not to interfere with users' natural behaviour in gestures.

CoVR is a Robotic Shape Display: it carries real objects and props. Real objects enable a high physicality (from our continuum Chapter 3), and interactions such as exploration or manipulation, and haptic features as wide as the ones proposed from the available props. CoVR also aims to enable whole-body interactions and postures, which is translated as a robustness specification (see Table 6.1). This robustness also can enable the use of heavy objects and large embedded masses. When designing CoVR, we ensured its navigation workspace was large enough to enable natural walking [Usoh et al., 1999], by integrating in a room-scale arena (see Table 6.1). The only interaction opportunity from Chapter 3 CoVR does not cater for is "Edition", which will be discussed in Chapter 8 (Future work).

We initially considered CoVR as a mobile robot, yet these devices are quite limited in speed, and cannot handle large force-feedback, or more specifically strong force feedback at a whole-body scale or different body postures.

We then deliberated upon a *grounded* solution, a 2D Cartesian ceiling-mounted robot, which can be integrated into a room-scale arena[2] (4x4x2.5m; *LxWxH*). The advantages are **speed, accuracy, force-feedback**, while allowing to move potentially heavy physical objects without the embedded mass affecting its displacements.

[2] The robot can be mounted on the ceiling or on an external truss structure (*triangle aluminum Global Truss*) as shown in Figure 6.2.

Another important consideration was the number of degrees of freedom (DoF) of the robot ($X - Y$ planar motion, $Z$ elevation, $W$ rotation around $Z$, 6DoF Robotic arm...). When dealing with robotic interfaces, a trade-off between price, complexity (and to some extent its deployment) and interaction opportunities can be drawn. Indeed, the more motors, the more expensive. Similarly, the more degrees of freedom, the more complex will be the control of the interface and even the safety measures to implement around the users. We pictured CoVR as a Proof-of-Concept, therefore criteria such as price or complexity were among our specifications.

We realised that a 2D planar motion carrying a modular structure already allows quite a large variety of scenarios while keeping a low technical complexity, with the benefit of being quite cheap to implement. More specifically, we decided to design CoVR as an modular, rigid and yet lightweight actuated column[3] use Do-It-Yourself materials. A column enables four different panels on which objects can be laid. The column can move in the whole virtual arena and carry physical props to match virtual objects the user is about to interact with. For instance, if a bottle and a glass are available in the virtual scene, the user can either decide not to interact, decide to interact with the bottle or with the glass. In the first case, the user will be free to walk without constraints. In the other cases, CoVR will direct itself to the chosen object of interest, and place itself prior to the user interaction. This principle hence enables a natural and intuitive way of interacting in VR.

[3] CoVR stands for a "Column in VR" that *covers* virtual objects with physical ones.

This chosen architecture can be extended with additional DoFs, which would make it more complex and expensive. For instance, a Kuka robotic arm would potentially reach the user's object of interest using its DoF instead of moving in the XY-area [Kim et al., 2018], however, a single XY-planar displacement shows to be sufficient and cheaper if its algorithm is robust enough to reach a targeted object of interest before the user.

In the following sections, we describe the main components of the final version of our system. We used an iterative process to design CoVR: at each iteration, we improved its robustness, accuracy, speed, safety, while widening the interaction opportunities (discussed and evaluated in Chapter 7). We then evaluate CoVR in a technical evaluation validating its control through a user **between-objects intention prediction** algorithm.

## 6.3 Hardware Design

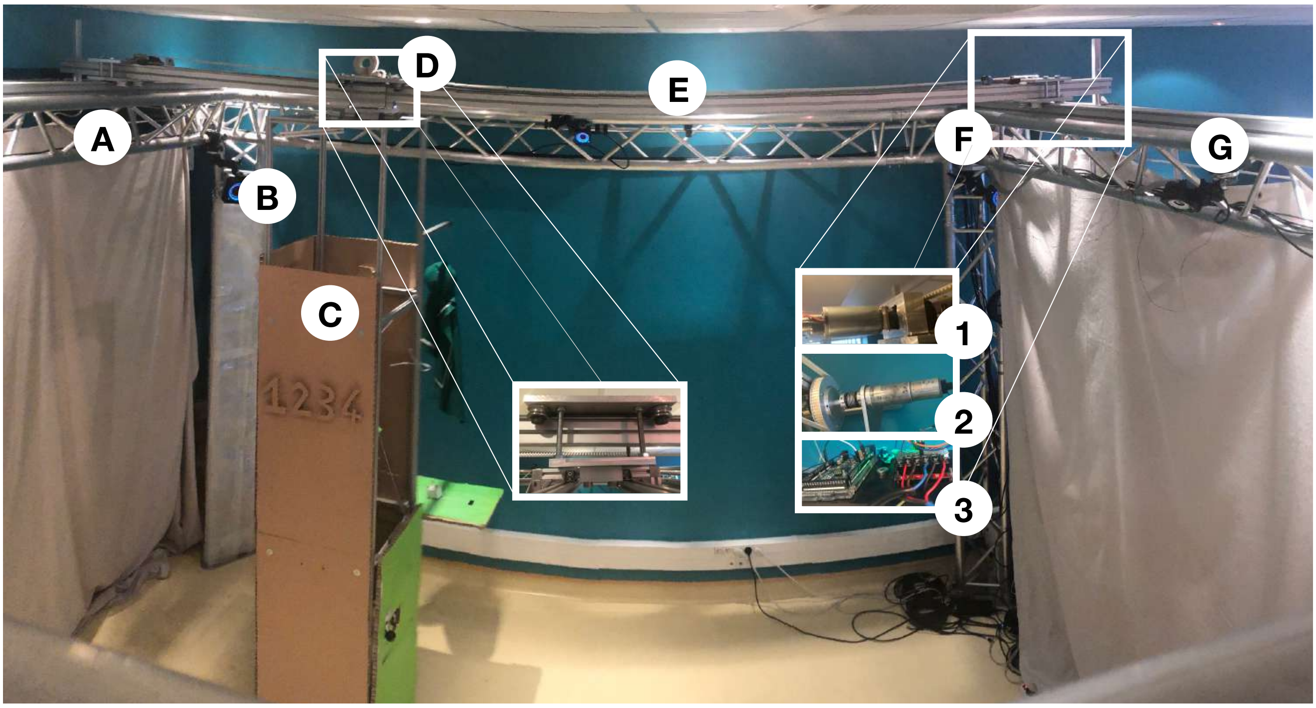



Figure 6.2: Top isometric view of CoVR setup: (A) Structure; (B) Skeleton, modular column-like structure to attach props and panels; (C) CoVR panel; (D) Carriage; (E) $X$-axis rail; (F) 1: $X$-Pulley-belt system and Motor, 1: $Y$-Pulley-belt system and Motor, 3 - Electronics (Arduino and RoboClaw); (G) $Y$-direction rail.

### 6.3.1 Robotic system

*Robot*. CoVR relies on a 2D Cartesian ceiling robot, actuated with DC Motors (*Dunkermotoren 55x30, KPL43 gearbox,*1.81*Nm torque for X-axis, Dunkermotoren 63x55, KPL57 gearbox,* 9.75*Nm torque for Y-axis*) through a pulley-belt mechanism (Figure 6.2). We chose a pulley-belt mechanism because it is simple to implement and can easily be scaled to larger VR arena. The robot moves a $15x15cm^2$ carriage on which is attached a modular structure (see Section 6.3.2).

The robot is controlled in speed with a *Roboclaw 2x30A V5E* motor controller and *AEAT-601B-F06* encoders, mounted on a custom-designed 3D-printed support. The Roboclaw controller is connected to an *Arduino MEGA 2560* micro-controller. It provides closed loop control with a *PIV*[4] scheme. The total price of the robot (motors, rails and pulley-belt) is under 1500euros.

[4] Proportional position loop Integral and proportional Velocity loop

*Speed.* The speed of the robot depends on the distance to travel. For large distances (> 1 m), the speed is over **1.1 m/s**, which is approximately a normal human walk speed.

For small distances (< 80 cm), speed is about 0.5 m/s, which remains faster than current mobile solutions (e.g. [Suzuki et al., 2020, He et al., 2017]).

*Accuracy.* We ran 100-cycle tests with the *PIV*[5] scheme, and had a 2.28*mm* accuracy (standard deviation = 0.6*mm*) at a 35Hz communication rate. The PIV controller enables to tune the acceleration/deceleration profiles and showed a negligible error compared to a PID controller. For the same speed, the PID error was about 23mm, i.e ten times bigger than the PIV one (2.28mm).

[5] Proportional position loop Integral and proportional Velocity loop

*Noise.* At full speed, CoVR's average noise is 55 dB average (max: 65 dB).

*Robustness, Weights and Forces Capabilities.* The carriage can support a total weight of 800*N* vertically and 1000*N* horizontally. The embedded mass the carriage can support is large enough (≈ 80*kg*) to support a human lying on it (≈ 100*N*) or even to be pushed by it without causing any damage to the structure. The system can also provide high traction force to pull the user or even transport her.

### 6.3.2 Column

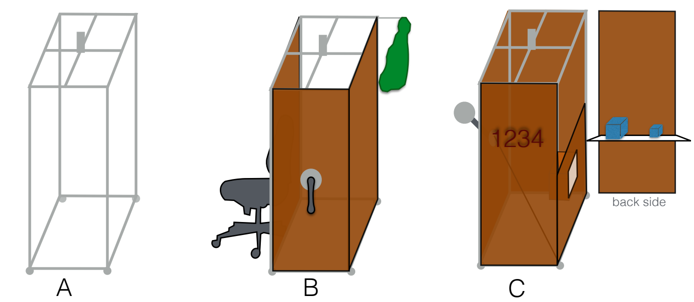



Figure 6.3: Column design. (A) Modular structure attached to the 2D ceiling robot to provide a wide variety of surfaces and props. (B) The 3-side column used in the user study with a chair (left), a cylinder attached to a spring virtually representing a broom (front), a large cardboard simulating a wall and piece of fabric representing a ghost (right). (C) A 4-side column implemented with a lever attached to the structure with an elastic (left), haptic code made in cardboard and glue (front), and a tray with a large and small cube (back) to insert into the locker (right).

A column-like modular structure (Figure 6.3-A) is attached to the moving carriage. Different surfaces in arbitrary positions, shapes, orientations and sizes can be attached using a simple clamping mechanism. It is similar to stage designing in real theatres [Pair et al., 2003], where a limited number of decors can quickly be replaced. Another advantage is to easily support *DIY*: the stage designer can use cardboard or props with different mass, textures and shapes that users can freely manipulate at different heights of the column. The positions and shapes of the physical objects are then communicated to the VR designer in a calibration phase.

In summary, the column was designed to be flexible enough to support a wide range of interactions. Figure 6.3-B and -C show two examples of implemented columns. The section Interactions and Demo Applications detail interactions with these columns.

### *6.3.3 Display and Tracking*

We use the Oculus Rift S [noa, 2019] HMD because it is not sensitive to occlusion problems and it allows interactions under or even in the column (Figure 7.7). We used Unity3D to create virtual scenes. It centralises the communication and synchronisation between different components though plugins (SteamVR, Arduino/Roboclaw). In particular, the SteamVR plugin asset [noa, 2019] is used for the Oculus communication and the Uduino package [Teyssier, 2019] for fast prototyping between Arduino and Unity. The Optitrack system allows to precisely and easily identify and track the position and the orientation of physical objects. The tracking space is 30 $m^3$ (3.5x3.5x2.5 $m^3$).

### *6.3.4 Safety*

As users are invited to move around an active large-scale mechanical system, safety measures had to be established. These were planned on several levels, from the structure conception to the motions around the users during interactions.

*Carriage:* The carriage can support both larger axial (800N) and radial (1000N) forces than those required for the envisioned scenarios.

*Column motions:* Hardware, software and electronic emergency stops are implemented. The carriage motion is restricted on both ends with spring-based mechanical stops. The software stops the motors when the column is within $2cm$ of these limits. The controller electronically shuts down when the motor's current exceeds $5A$. More importantly, the column immediately stops if the user is not tracked for more than 0.5s. Finally, the *game master* has a manual emergency stop button that turns the system off, keeping it electrically grounded to avoid potential shocks. Finally, given the power and speed of the robot, it is important to ensure the column will not accidentally physically collide with the user. We implemented this in our trajectory generation software (Section 6.4).

## 6.4 Software Design

As opposed to Chapter 5, where the intention model is within-objects, this software section is to be considered as a complement, as it is between-objects. Similarly to the model in Chapter 5, it also can be used with other ETHDs. It aims to (1) facilitate the control of interfaces and (2) enable these interfaces to perform non-deterministic scenarios, i.e. scenarios where the system does not know beforehand which object to physically overlay. It covers the following questions:

- *How to control the interface?*
- *How to anticipate the users next interactions?*

### 6.4.1 Robot Motion Control

We present a model to control the robot displacements. While trajectories are easily generated by the Cartesian structure (XY displacements), the algorithm inputs for scenarios involving multiple objects of interest need to be defined and safety measures around the user need to be implemented. The robot can be controlled in a simple position scheme, without any regards concerning the user (such as in our first user study, Section 7.5); or in a more complex mode including obstacle avoidance and weights, (such as in our second user study, Section 7.6)[6]. This mode is inspired from robotics trajectory control techniques using potential fields [Khatib, 1986], combined to mechanical spring-damper models used to couple a simulation engine and a real robot in real-time [Bayraktaroglu et al., 2019]. The key idea is to drive the robot following the motion of a virtual proxy that takes advantage of Unity's physics engine. We first describe the behaviour of the virtual proxy and trajectory computation with weights. We then describe how to couple the robot to the virtual proxy.

[6] Both of these studies are in Chapter 7.

*Virtual proxy*. The proxy is a virtual rigid sphere with mass, hence subject to gravity and Newtonian physics. It is placed on a flat surface in an invisible layer of the game engine covering the arena. It is free to roll on this surface under the effect of external forces, can fall into slopes and avoids climbs.

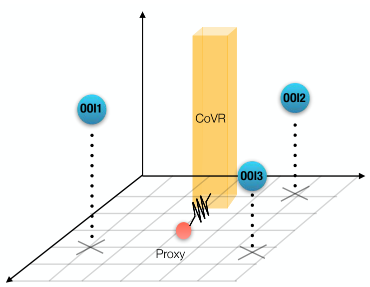



Figure 6.4: Control algorithm relying on a physical model: CoVR is attached to a virtual proxy - a ball rolling on the floor and subject to Newtonian physics, with a spring-damper model.

*Motion coupling of CoVR with the proxy*. The physical robot is coupled to the virtual proxy by using a spring-damper model to calculate the set-point velocity vector $\vec{V_c}$ to be sent to the low-level controller (see Figure 6.4):

$$\vec{V_c} = k_p \times \vec{RP} \tag{6.1}$$

where $\vec{RP}$ is the position vector from the robot to the proxy and $k_p$ the coupling stiffness. $k_p$ is chosen empirically as to minimise the following error between the proxy and the robot. This virtual elastic coupling generates a velocity vector on the robot, pushing it towards the proxy at every frame. The column hence reproduces quite faithfully the proxy's trajectory.

The proxy's displacements depend on (1) the user's location - to avoid collisions, (2) the user intentions and (3) the progress of the scenario - it should be attracted by objects users are most likely to interact with next. A key contribution regarding our trajectory generation model is the elaboration of a low-computational **between-objects user intention prediction model** working with common HMDs. We now detail our approach to generate trajectories.

*Trajectory generation.* Each virtual object of interest $i$ within the scene gets a weight $W_i$ which depends on its likeliness to be interacted with next. The virtual proxy (ball) and CoVR command position $CoVR(x,y)$ is hence a weighted average of the positions of each object of interest:

$$CoVR(x,y) = \frac{\sum_{i=1}^{N} W_i * (x_i, y_i)}{\sum_{i=1}^{N} W_i} \tag{6.2}$$

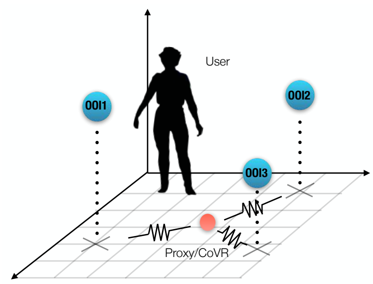



Figure 6.5: Control algorithm relying on a physical model: The proxy is attached to all of the available objects. Its position is defined by a weighted average of each OOI positions.

where $N$ is the number of virtual objects of interest (OOI) in the scene, $(x_i,\ y_i)$ the cartesian coordinates of the OOI $i$ and $W_i$ its weight, estimated given a user intention model (see below). A virtual spring between the proxy and the command position is then defined, and the according spring force is applied for the proxy to reach this position. We use Unity3D's physics engine to automatically generate the proxy trajectories to reach a target. The target position is not necessarily the position of a virtual object. If the scene contains two objects of same interests, CoVR will automatically place itself between these two objects' positions, hence the displacement when one becomes the chosen object of interest is minimised and CoVR is more likely to reach it prior to user interaction. As the proxy is also attached to CoVR, its resulting motion takes naturally into account the robots speed limitations.

*Avoidance.* Virtual **obstacles** cover all forbidden areas in the arena and one is attached to the user. A cone-like rigid shape (radius= 90cm[7]) with a base-curvature tangent to the horizontal axis is used (Figure 6.6). Thanks to the contact mechanics and gravity in the physics engine, the proxy (a sphere), is naturally pushed and rolls away from the obstacle. The obstacle's curvature ensures a smoothly deceleration of the proxy when this latter is getting to close to it. The radius of the obstacle

[7] The size of the cone was chosen to avoid collisions even if the users' arms are open.

decreases (20cm) when the user comes near a *OOI*, so the proxy is not pushed away. It disappears whenever the proxy reaches the users chosen *OOI* - as it is not required to move anymore. The curvature of the obstacle can also be decreased to let the proxy come closer, if a sufficient force towards the user is provided. These virtual obstacles can be added to furniture, users or even pets - basically all forbidden areas within the arena. It is necessary to track any body that CoVR might run into in the VR arena.

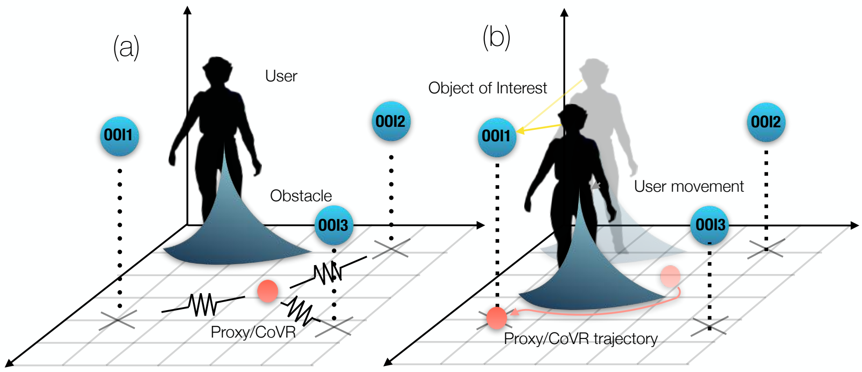



Figure 6.6: Control algorithm relying on a physical model: (a) The virtual proxy of the physical CoVR column is connected to all virtual objects of interest (OOIs) with weights depending on the users' intentions to interact with them. The user and other forbidden zones are covered by a rigid cone-like obstacle to be repulsive. (b) Whenever the user is about to interact with a OOI, the proxy/CoVR move towards it, while naturally avoiding obstacles (e.g the user).

Using this mechanical approach, other motion control strategies are possible. For example, a height-map on the floor would privilege some trajectories.

The main advantage of this implementation is to abstract the robot motion control using physical elements in the simulation engine. It hence becomes easy to conceptualise scenes on the designers' side. They only need to directly manipulate the proxy integrated in the VR engine, without requiring any low-level access to the robot. The use of simple elements such as springs and slopes makes imagining trajectories quite straightforward and hides the complexity of the robot control. Also, thanks to the physics engine, experimenting trajectories resulting from different intention weights, OOI positions and scenarios is safe and accurate solely by observing the virtual proxy's motion, without using the real robot.

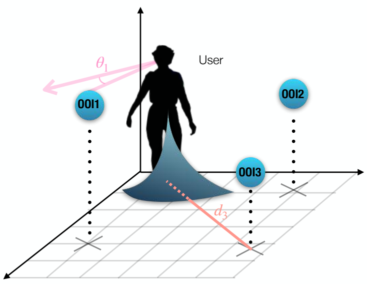



Figure 6.7: $\theta_1$ is the angle from the user's orientation and its closest point over OOI1; $d_3$ is the distance from the user and OOI3.

### 6.4.2 *Between-Objects User-intention Model*

As previously mentioned, we elaborated a between-objects user intention model to support non-deterministic scenarios.

The model inputs are the positions of the virtual objects of interest (OOI) as well as the available data from the users' apparatus: the HMD's position and orientation. It hence does not require additional hardware such as eye-tracker or finger/hand tracker. The output is the user's object of interest among distractors.

We defined the total weight $W_i$ of the OOI $i$ to be a function of the user's distance $D$ to a OOI, and her orientation ($O$).

$$W_i(d,\theta) = \omega * D(d) + (1-\omega) * O(\theta) \quad (6.3)$$

$$W_i(d,\theta) = \omega * \frac{1}{1+d} + (1-\omega) * e^{(cos(\theta)-1)} \quad (6.4)$$

where $\omega$ is the contribution of the distance over the orientation. $D(d)$ and $O(\theta)$'s ranges are between 0 and 1, hence $W_i$'s range is from 0 to 1 too.

$O(\theta)$ is equal to 1 whenever the user's HMD orientation is colliding with any surface point of the OOI's mesh, and is decreasing exponentially whenever the user's orientation moves further away. On the same principle, $D(d)$ is equal to 1 whenever the user is close to a target, and decreases with the same regards[8](see Figure 6.7).

[8] We also increase the stability of the column in the vicinity of the OOI. When $W_i > 0.8$, $W_i$ is rounded to 1, typically when an object is at less than 20 degrees from the user's HMD direction or when the object is at a distance below 20cm from the user. It allows for CoVR to stay at the closest OOI as long as the user remains in its vicinity.

### *6.4.3 Scenario-based Model*

Depending on the progress of their scenario, designers can estimate the prior probability of an object to be interacted with: in a basketball game for instance, the user is more likely to interact with the ball first than with the hoop. We let the possibility to designers to define their own scenario-based model by refining the estimation of $W_i$:

$$W_i = P_i \times W_i(d,\theta) \quad (6.5)$$

where $P_i$ is the prior probability of the OOI $i$ to be interacted with from the progress of the given scenario.

We will discuss the use of these probabilities in the Discussion section of our Technical Evaluation below (Section 6.5.4).

## *6.5 Technical Evaluation*

The primary aim of this technical evaluation is to determine the $\omega$ parameter of the user intention model, i.e. the optimal contribution of the distance over the orientation to estimate which object of interest is more likely to be interacted with. We are also interested in studying CoVR's success rate as a function of the number of objects of interest (*distractors*) within the scene. Indeed, we anticipated that the performance of the user intention model and the value of $\omega$ depend on the number of distractors within the scene. Finally, we want to confirm that CoVR's speed is sufficient enough to reach a virtual object of interest even when the user does not have a decision to make (number of OOI = 1).

We first perform a data collection over a panel of users to better understand how intentions can be quantified as a function of both distance and orientation. We then perform multiple physical simulations to find the best $\omega$ parameter that matches users' behaviors.

### *6.5.1 Data Collection*

#### *Participants and Apparatus.*

Six participants (3 male, 1 left-handed) aged from 26 to 32 (average = 28; std = 2.0) volunteered for this experiment. All participants were familiar with VR and were asked to wear the Oculus Rift S. Users also wore Optitrack markers on their dominant hand. The Oculus headset was also equipped with Optitrack markers, for an accurate tracking in space. The virtual scene was created using Unity3D game engine.

#### *Experimental Design*

*Task and Stimuli.* We considered an exploratory task, such as the ones users would perform in games, i.e. users take their time, observe the decors, avoid virtual obstacles and face their objects of interest whenever interacting. To replicate these game features and to capture the corresponding users' behaviors, we created an empty scene where virtual numbered balls appear simultaneously at random locations with random orientations (see Figure 6.8). Instructions are written on the walls surrounding the users, and tell them to touch a given numbered virtual target. Users are then asked to face the targets whenever touching them.

*Conditions.* In this experiment, we control the number of distractors within the scene from 0 to 4 (number of balls is from 1 to 5). This allows us to understand the performance of CoVR over the number of available OOIs. The minimum distance between two targets is their diameter - 10cm (eg they cannot overlap) and they cannot appear at the user's location. As long as the user does not touch the target ball, nothing changes in the scene. As soon as the target ball is interacted with, another condition starts.

*Design.* We used a within design. All participants tested all five conditions (0,1,2,3,4 distractors). The order of appearance of each condition was randomized within the blocks. Participants performed 10 blocks. The duration of the experiment was about 12 minutes per participant (std = 2.6). In summary, the experimental design is: 6 participants $\times$ 10 blocks $\times$ 5 conditions $=$ 300 trials.

For each trial, we measure the users' position and orientation at each frame, with a frame rate of 75 fps.

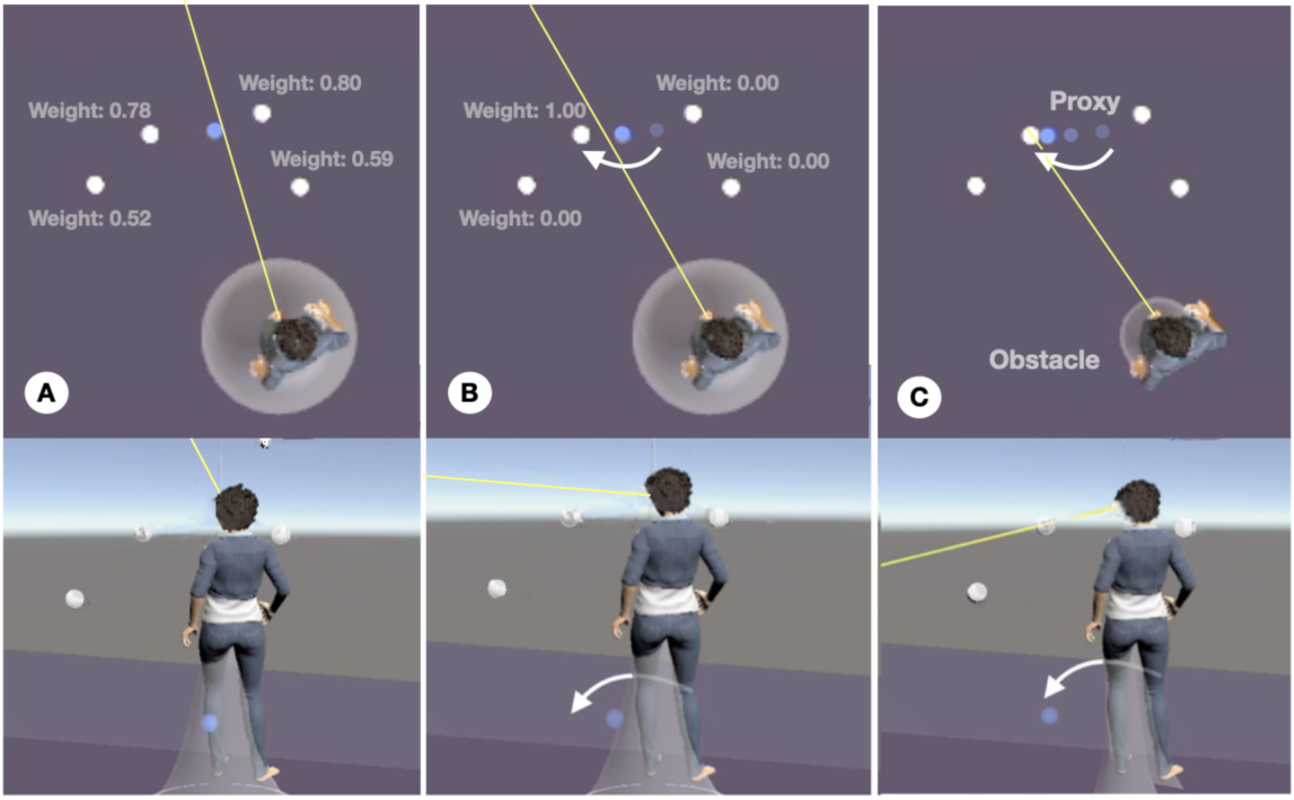



Figure 6.8: Technical Evaluation *"Simulation"* Virtual Scene example after the Data Collection. (A) User looks for the target (according to the walls' instruction). Weights change according to her position and orientation. (B) *Intention Detection*: User chooses a target and its weight goes to 1. (C) *Trajectory*: The proxy (blue ball) moves accordingly with the centroid of all the objects' of interest's weights towards the chosen one (weight = 1), while avoiding the user obstacle. When the proxy reaches the chosen ball, the user obstacle size decreases.

### 6.5.2 *Parameter Fitting*

We used the data collection to replicate the users' displacements into a Simulation virtual scene. The robotic system physically moved accordingly with our "user intention model" (section above). Each simulation corresponded to a different $\omega$. We simulated all the data from the 6 participants (i.e. including the 5 conditions). We first performed a broad exploration of $\omega$ (step= 0.25) and then refined it to find the optimal one for each condition (number of distractors in the scene). We tested 13 parameters over 6 users, which resulted in more than 17 hours of simulation.

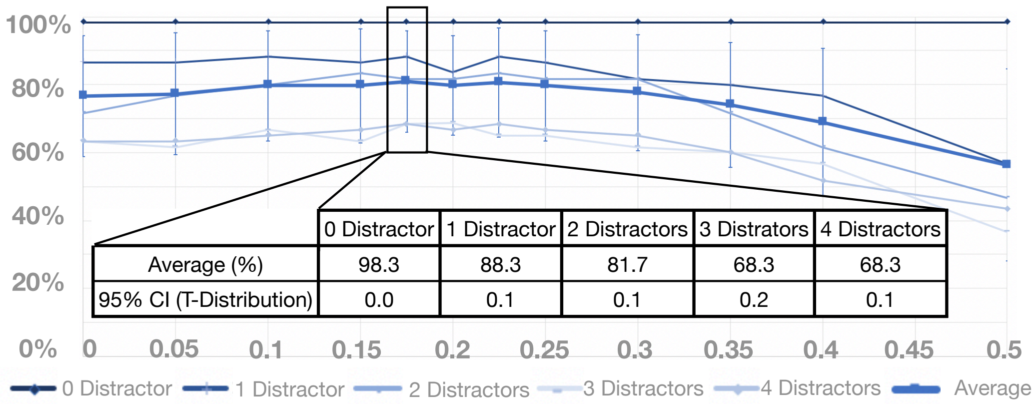
Our main measurement was the success rate of CoVR reaching a OOI before the user, i.e. when CoVR's distance to the target was below its diameter (10cm) when the user was touching it.

### 6.5.3 Results

#### *Success Rate*

Figure 6.9 shows the success rate as a function of $\omega$ and the number of distractors. The success rate is approximately 100% (only 1/300 targets missed) when there is only one OOI in the scene, indicating that the system is at least as fast as the participant when the target position is known (i.e. the system does not rely on the users' intention). The results also confirmed that the success rate decreases with the number of distractors. Figure 6 also shows that we obtain the best average success rate (80%) with $\omega = 0.175$ (CI=14%) regardless of the number of distractors. Success rate remains above 80% up to 2 distractors.

We also note that the success rate per user increased with the time spent in the experiment (88% success for a 14mn experiment vs 74% for an 8mn experiment).




| | 0 Distractor | 1 Distractor | 2 Distractors | 3 Distrators | 4 Distractors |
|---|---|---|---|---|---|
| Average (%) | 98.3 | 88.3 | 81.7 | 68.3 | 68.3 |
| 95% CI (T-Distribution) | 0.0 | 0.1 | 0.1 | 0.2 | 0.1 |

Figure 6.9: Success Rate of CoVR reaching the chosen OOI prior to the user interaction, function of $\omega$ and the number of distractors. Error bars indicate 95% confidence interval with a T-Distribution. The table shows the Success Rate with the optimal parameter, $\omega = 0.175$, as function of the number of distractors.

#### *Target distance*

We measured the average distance between the carriage and the target centres when the user was colliding with the virtual target. The average distance among all the trials is 1.8cm (95% CI = 0.33 cm) demonstrating the repeatability and precision of our implementation. We discuss how to improve it in the Discussion section below (Section 6.5.4).

#### *Detection time*

We also measured the time difference between the target's weight reaching 1 and the user colliding with it. Results show that this detection time does not depend on the distractors, with a 7s average (std = 0.6s) and a 96% accuracy. We note that if the detection time is below 4s, it results in a failure of the overlaying, as CoVR struggles to get around the user (especially the obstacle), to eventually and place itself properly.

*Number of users collision*

No collision between the user and CoVR were noted during the simulations. This demonstrates that our model is valid and safe around the user.

*Accuracy*

Finally, we measured the distance between the virtual proxy and the physical column. The mean distance over all users and conditions is 0.94 cm (CI 95% = 0.99 cm), which ensures they share the same trajectory, and hence a safe user environment around CoVR.

| | 0 Distractor | 1 Distractor | 2 Distractors | 3 Distrators | 4 Distractors |
|---|---|---|---|---|---|
| Average (cm) | 0.6 | 0.9 | 1.0 | 1.2 | 1.0 |
| STD (cm) | 0.4 | 0.7 | 0.8 | 1.0 | 1.0 |

Table 6.2: Accuracy, measured by the distance between CoVR and the proxy, with $\omega$ = 0.175.

### 6.5.4 *Discussion*

This evaluation tested CoVR in an uncontrolled environment, with **random** locations and orientations for each target and distractor and a user-intention based model. Despite this environment, our system had a high success rate ($>$ 80%) with three virtual objects of interest while preserving the user's safety (no collision). Similarly as in Chapter 4, where we depict solutions to mitigate some failure effects, we propose in this subsection solutions to increase our algorithm success rate.

*Adding a scenario-based model*

According to the Equation 6.5, we can add "prior probabilities" to the different OOIs, depending on the progress of the scenario. After selecting our optimal parameter $\omega = 0.175$, we ran the robotic simulation by adding to the actual target a 75% probability to be interacted with. The distractors were hence splitting the remaining 25% of interaction probability. The results are summarized in the Table 6.3 and confirm that adding a scenario-based model improves the prediction with a success rate higher than 93% even with four distractors.

Table 6.3: Success Rate and Distance to Target with $\omega = 0.175$, and a 75% probability to be interacted with added on the target.

| | 0 Distractor | 1 Distractor | 2 Distractors | 3 Distrators | 4 Distractors |
|---|---|---|---|---|---|
| Average % (95% CI T-Distribution) | 98.3 (1.8) | 95.0 (2.4) | 93.3 (4.4) | 96.7 (3.5) | 93.3 (3.5) |
| Average Distance to Target (STD Distance, in cm) | 0.4 (1.4) | 0.7 (1.7) | 0.6 (1.6) | 1.0 (1.8) | 1.2 (2.2) |

### *Assigning multiple OOI to the same Physical position*

Thanks to its size and shape, CoVR can contain multiple objects on different panels and at different heights. We can take advantage of this feature to assign multiple virtual objects of interest to the same physical location, hence reducing the amount of CoVR displacements and the risk of spatial mismatches.

### *Adding visual effects*

When a spatial mismatch is likely to occur, literature usually proposes to cater for it with visual effects [Cheng et al., 2015]. These were described in Chapter 4, as they distract the users and give spare time to the robot to reach the target location.

### *Redirecting the hand with Within-Object Intention information*

The redirection solution [Azmandian et al., 2016] was thoroughly described in Chapter 4. The distances between the target and carriage centres were of an average of 1.8cm, which is small but can be tackled by orienting the users' hands towards their absolute within-object interaction intentions, using the model proposed in Chapter 5).

## *6.6 Conclusion*

We presented CoVR, a Robotised Tangible User Interface providing Haptic feedback in VR, anticipating intentions to physically encounter the users. CoVR's displacements are controlled by a between-objects user intention prediction model, to physically overlay the users' expected virtual counterpart prior to interaction.

Software-wise, it **predicts** which object of interest to overlay in non-deterministic scenarios between-objects, and **where** the interaction will occur, within this object. Hardware-wise, we showed CoVR was fast and accurate enough to physically overlay the users' objects of interest prior to interaction, and its trajectories naturally avoid users. Its implementation also demonstrates a good robustness. As depicted in Chapter 4, the classic Robotic Graphics scenario goes through three steps: Intentions, Displacement, and Interaction.

In this chapter, we exploited our Analytical Framework (Part I) in order to define CoVR specifications. For instance, we traded CoVR's between-objects user intention prediction algorithm with its mechanical capabilities. mechanical properties.

We can summarize CoVR current capabilities according to the criteria from Chapter 3 in the following table (Table 6.4)[9]:

[9] CoVR will be fully compared with the other interfaces from Chapter 3 in the next chapter.

| | Interaction Opportunities | | | | | | Physicality | Modularity | | | | Actuation & Robotics | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Navigation Workspace | Haptic Features | Exploration | Manipulation | Edition | Whole-Body Involvement | Passive Haptics | Number of Props | Operator | Non-Deterministic Scenarios | Deployment Use-cases | Robustness | Accuracy Speed | Safety | Ease-of-Use |
| CoVR | 30 $m^3$ | Defined in the subsequent chapter | | | | | Yes | Prepared prior to use | Yes | +++ | Arcade, Training | +++ | ++ | + | +++ |

Table 6.4: CoVR according to the Criteria for Analysing Robotic Graphics interfaces, from Chapter 3.

These two first chapters of Part II were with a global designer perspective. We can then summarize CoVR current capabilities according to the Conception requirements from Chapter 4:

- CoVR anticipates **which** objects to physically overlay **between** objects, and where the interaction will occur **within** objects.
- CoVR reaches the chosen object of interest **prior** to the user, **accurately** and **reliably**.
- CoVR **safely** avoids the user during its displacement.
- CoVR displays the **adequate prop**.

In the next and final chapter of this Part about CoVR (Part II), we will define CoVR's interaction opportunities, and ultimately evaluate CoVR with a user perspective.

WHAT YOU MUST REMEMBER

*Contributions:*

– A replicable *software brick* predicting the users future objects of interest prior to interaction.
– CoVR's implementation (Hardware and software), minimising spatial mismatches in non-deterministic scenarios while preserving the users safety.
– A technical evaluation validating a user intention quantification for controlling Encountered-type of Haptic devices in VR.

7

# Interaction Opportunities and Studies

CoVR is a Robotised Tangible User Interface, anticipating the users' intentions between multiple objects of interest, and within a single object of interest. It displaces itself to physically overlay virtual counterparts in VR. From the Robotic Graphics classic scenario in Chapter 4, CoVR is thus defined for the Step #1: Intentions, and Step #2: Displacement. This chapter focuses on the Step #3 of the scenario: **Interactions**.
When *no interaction is required*, CoVR remains out of reach and the users can wander in the whole arena. CoVR thus does not interfere with users' natural behavior. Letting the users truly walk reinforces their immersion [Usoh et al., 1999]. This chapter focuses on CoVR *when interactions are required*.

CoVR being the *Haptic Solution* from our Triangular approach, we can identify its associated questions from a *Haptic Feedback* and *Haptic Interaction techniques* categories in Figure 7.1.

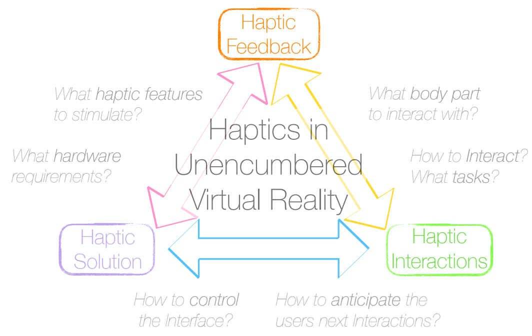



Figure 7.1: CoVR is the Haptic Solution of the Triangular approach. Remaining questions are:
What haptic features to simulate?
What body part to interact with?
How to Interact? What tasks?

In this final chapter of the CoVR-related part (Part II):

– At a *Haptic Solution* and *Haptic Feedback* intersection, we demonstrate that CoVR can be used to provide large-scale kinesthetic feedback from its structure, but also hand-scale tactile feedback by providing a high level of physicality.

– At a *Haptic Solution* and *Haptic Interactions* intersection, we propose to take advantage of CoVR's displacements to create novel interaction techniques in VR. Inded, we can depict two categories of interactions with CoVR: when CoVR is *static* and when CoVR is *dynamic*.

– At a *Haptic Feedback* and *Haptic Interactions* intersection, we show that CoVR can be used for bare-hands interactions but also involves the whole-body. We analyse the various tasks CoVR enables in VR and their associated interaction techniques. Finally, we conduct user evaluations to empirically define the haptic feedback consistency as well as which interactions users enjoy the most.

## *7.1 Approach*

In this chapter, we use our Analytical Framework (Part I) to depict CoVR's interaction opportunities and design its evaluation protocols.

We first use CoVR's mechanical implementations to define its associated interaction opportunities. For instance, in Chapter 4, we defined how the conception and perception phases are related: a high robustness will enable large embedded mass to eventually provide users with their expected perceived stiffness. In the same regards, in this chapter we take advantage of CoVR's displacements to provide the users with novel interaction techniques. We extract the interaction opportunities from Chapter 3 to define the interactions CoVR enables. We finally use the foundations from Chapter 2 to define our evaluation protocols.

## 7.2 Interaction Opportunities

In this section, we use the Interaction opportunities from Chapter 3 and the associated *Technique* when using CoVR.

### 7.2.1 Navigation

As mentioned in Chapter 6, CoVR's arena is over $30m^3$, which enables the users to perform *"Real Walking"* to navigate in the arena.

CoVR also enables a novel technique to navigate in VR: *transportation*. Indeed, CoVR mechanical properties enable to literally transport users: as it can handle large embedded masses (≈ 80kg), it can move a chair with a sitting user to a different location (Figure 7.2). We can picture scenarios where dynamic displacements are relevant, for instance with sports such as wind-surfing, kite-surfing, paragliding.

Figure 7.2: The user can be transported by CoVR, making physical and visual dynamics match.

### 7.2.2 Exploration

Hands remain the primary body part for exploring the world and the most sensitive one. As CoVR is designed to enable Unencumbered Interactions, we can deduct that Exploration with CoVR is performed through *"Real Touch"*.
CoVR enables users can probe objects directly with their bare-hands. As such, interactions are not limited to one finger: surfaces can be realistically touched and their texture fully felt with the whole hand, with both tactile and kinesthetic cues. Moreover, the explored surface can be large and not limited to a specific orientation or shape. For instance, users can perform large hand movements to find a specific tactile pattern on a wall (Figure 7.3-A).

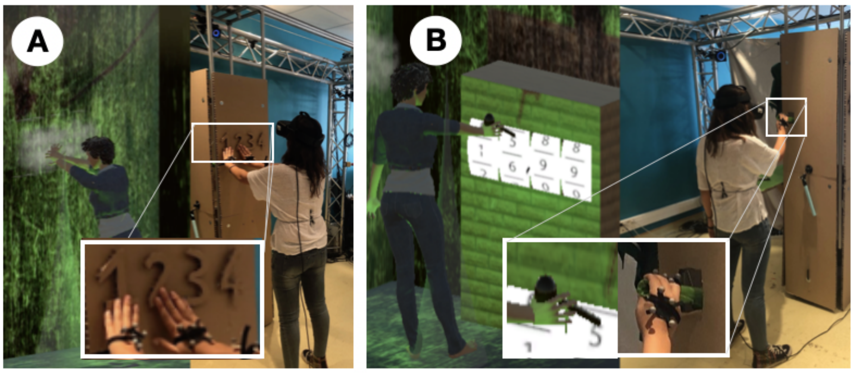



Figure 7.3: (A) Tactile Exploration: The user tactilely explores large surfaces, for instance, to find a hidden code over a human-sized wall. (B) Directed Manipulation: The user pulls a lever which is attached to CoVR with an elastic, letting it a single degree of freedom, providing a mechanical manipulation of props.

### 7.2.3 Manipulation

CoVR enables "Direct Manipulation", which relies on the ability to hold an object with kinesthetic feedback, "much as objects are manipulated in the real world" (cf Chapter 3). This manipulation of real objects and passive props improves interaction fidelity [Rogers et al., 2019, Insko, 2001]. We distinguish different types of object "direct manipulation" using CoVR:

- *Free manipulation*. CoVR can carry untethered objects which users can grab and freely manipulate. A large variety of samples (Figure 7.4-B) of any textures is possible, as long as dimensions and weights are compatible. Thanks to the CoVR's grounding and high motor torques, it can carry large masses without compromising its speed or accuracy. The haptic transparency of the feedback is thus ensured whether the users wants to interact with a light or heavy prop.
- *Contact*. Objects can also be manipulated to interact with each other. For instance, in Figure 7.4-C, the big cube does not physically fit in the locker. The user hence needs to find a smaller one.
- *Directed manipulation*. Users can interact with objects tethered to CoVR. Its structure allows for mechanical manipulation of objects and for users to actuate them. For instance, in Figure 7.3-B, the user actuates a lever mounted on the column, simulating a slot machine;and in Figure 7.4-A, she physically opens a door. By attaching objects on CoVR's skeleton, mechanical manipulation with multiple numbers of degrees of freedom is possible.

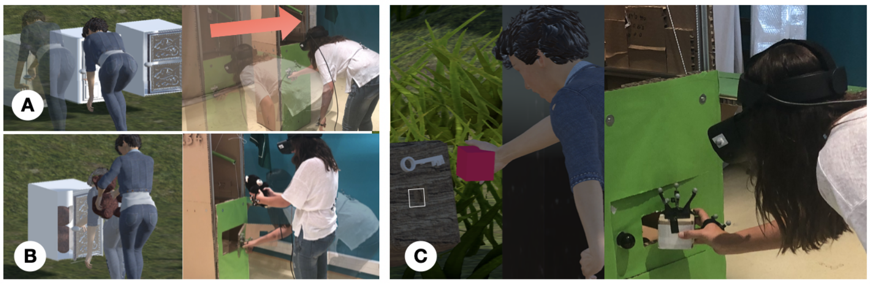



Figure 7.4: (A) Directed manipulation; User opens three virtual doors - but only a single physical one, cut through a panel cardboard. (B) Free manipulation; User finds a teddy bear. (C) Free manipulation and Contact; The user manipulates a cube which is too big to fit in the locker. She realises she needs to find a smaller cube.

A single physical object can overlay multiple virtual ones of similar primitives [Hettiarachchi and Wigdor, 2016]. In addition to using visual effects such as [Azmandian et al., 2016], CoVR physically moves a single prop to overlay multiple virtual ones. For instance, one physical door can overlay three virtual ones (Figure 7.4-A). These correspond to the $< virtual : physical >$ mappings introduced by McNeely for Robotic Shape Displays, and evoked in Chapter 4 (Section 4.3.3).

### *7.2.4 Edition*

CoVR is a Robotic Shape Display: it exploits real props and objects to provide a high level of physicality. At the moment, only "Pseudo-Edition" techniques could be employed with CoVR (but are not implemented). Enabling "Physical Edition" using CoVR is discussed in our Perspectives chapter (Chapter 8).

### *7.2.5 Environment-Initiated Interactions*

We distinguish two scenarios here: either CoVR interacts with the user, which receives an *external* physical contact; *or* the user is already interacting with CoVR, and CoVR then leads the user through forces.

#### *Receiving External Physical Contact*

CoVR can physically touch the users and produce impact force feedback [Wang et al., 2020]. It is thus initiating the haptic interaction, instead of the user. As receiving an interaction might be surprising in VR, we recommend attaching props at a distance from CoVR's main skeleton, to produce light impact forces. For instance, a fabric (60cm away from the main skeleton) can lightly brush the users to simulate the crossing of a ghost (Figure 7.5 - 1) through them. Users can also be touched by a virtual agent trying to catch their attention, providing a sense of physical presence [Lepecq et al., 2008, Hoppe et al., 2020].


Figure 7.5: Environment-Initiated Interactions: 1. *Receiving Physical contact*: A fabric is about to slightly brush the users' head to simulate a virtual ghost. 2. *Leading through forces*: CoVR is strong and robust enough to pull the users through forces and to provide large force-feedback.

#### *Leading through forces*

Users can also be led by CoVR through body-scaled tension and traction forces. For instance in Figure 7.5 - 2, the user physically holds a cylinder attached by a spring to the column (virtually represented by a broom), which provides her with a large force-feedback and leads her the way in the virtual environment. She is pulled by the broom when CoVR moves. Another example is inspired from [Cheng et al., 2017], involving a fishing pole where the line is attached to the column. The motion of the column creates the illusion of a fish biting.

### 7.2.6 Whole-Body Involvement

Users can apply strong forces with any part of their body: users can push hard on a wall with their hands or shoulders (Figure 7.6 - 1), lean on a it (Figure 7.6 - 2), or even kick it. CoVR is rigid and robust enough to remain still during all of these interactions.


Figure 7.6: Whole-Body Interactions: (1). Pushing on a wall or (2). leaning on it.

CoVR also supports a variety of users' postures illustrated in Figure 7.7, with interactions at different heights such as sitting on a chair (-1), climbing a stair to reach a high target (-2), crouching under a table, going through obstacles with physical props both below and above the users (-3,4).


Figure 7.7: Postures; The user (1) sits comfortably on a chair: (2) climbs a step to reach a high physical prop, (3) goes through an obstacle with constrains below and beneath her (4) or crouches.

> From all of interactions CoVR proposes, we distinguish two main uses of CoVR: **static** use where users transmit forces when interacting with the column (e.g. exploration, manipulation) and **dynamic** use, where users are receiving forces enabled by CoVR's displacements during the interaction (e.g. leading through forces, transport) (as depicted in Figure 7.8).
> CoVR introduces novel interaction techniques from its *dynamic use*, such as *transport* or *being led through forces*. These rely on stimulating the users *kinesthetic cues* through *large force-feedback* and *whole-body involvement*.

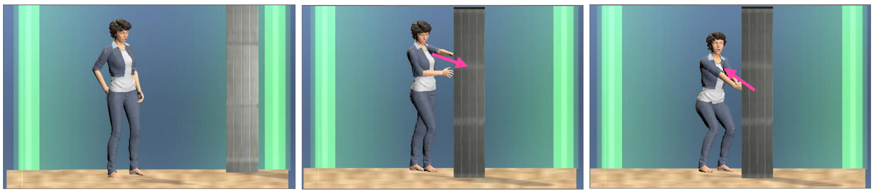



Figure 7.8: When no interaction is required, CoVR remains out of reach so the user can wander in the whole arena. When an interaction is required, we distinguish static and dynamic interactions.

## 7.3 Evaluation Protocols

From Chapter 2, we defined that quantifying *presence* - the feeling of being in another place than the one we are currently in - through questionnaires are the normalized protocols to evaluate Virtual Reality experiences. Yet, we concluded that presence questionnaires were not thorough enough to evaluate haptics in VR and its associated opportunities. We suggested that protocols should be required to evaluate Haptics in VR through *Haptic Solution*, *Haptic Interaction Techniques* and *Haptic Feedback* categories, and suggest dimensions to explore.

Regarding the *Haptic Solution* perspective, we depicted CoVR's capabilities in Chapter 6. We report them in a first analytical study of CoVR, along with additional dimensions suggested in Chapter 3.

Regarding the *Haptic Interaction Techniques* and *Haptic Feedback* perspectives, we conduct two User studies. First, we quantify *presence* using CoVR, to compare bare-hands interactions (real touch, direct manipulation) to controllers. We also conduct semi-structured interviews to qualify the users tactile feedback. Second, we propose a two-scene demo application involving various whole-body postures and large force-feedback. We quantify the kinesthetic feedback users receive from CoVR's *dynamic interactions* and show that users enjoy these interactions the most. In these user experiences, we also report on CoVR's performances, by evaluating whether its mechanical implementation and algorithm are robust enough.

## 7.4 Analytical Study

We evaluated CoVR in Chapter 6 according to the Robotic Graphics 4 of our Analytical Framework (Part I). Similarly, Chapter 3 suggested dimensions to evaluate and compare *Haptic Solutions* in VR. These were centered over 4 categories: Interaction Opportunities, Physicality, Modularity, and Actuation & Robotics. In Table 7.1, we summarize CoVR capabilities, and compare it with the three previously evoked Robotic Graphics interfaces.

| | Interaction Opportunities | | | | | | Physicality | Modularity | | | | Actuation & Robotics | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Navigation Workspace | Haptic Features | Exploration | Manipulation | Edition | Whole-Body Involvement | Passive Haptics | Number of Props | Operator | Non-Deterministic Scenarios | Deployment Use-cases | Robustness | Accuracy Speed | Safety | Ease-of-Use |
| Beyond the Force | $2m^3$ | ++ | ++ | + | - | - | Yes | Prepared prior to use | Yes | - | / | - | - | - | +++ |
| ShapeShift | Desktop | + | +++ | + | + | - | No | ∞ | No | ++ | 3D Terrain Volumetric Data | ++ | + | +++ | +++ |
| Snake Charmer | Desktop | +++ | +++ | ++ | - | - | Yes | Prepared prior to use | No | ++ | Training | + | + | ++ | +++ |
| CoVR | $30m^3$ | +++ | +++ | +++ | - | +++ | Yes | Prepared prior to use | Yes | +++ | Arcade, Training | +++ | ++ | ++ | +++ |

Table 7.1: CoVR compared to other Robotic Graphics interfaces according to the Criteria for Analysing Robotic Graphics interfaces, from Chapter 3.

CoVR provides a room-scale arena, which benefits the Navigation, especially compared to the other proposed interfaces. CoVR can simulate various haptic features, as it benefits from the use of real props. It can display props of various textures, shapes, or even weights. It enables both real touch exploration and direct manipulation, with a high haptic transparency. The drawbacks of this real prop exploitation remains in the Edition task, which CoVR does not enable.

Even though CoVR requires an operator to design and change its panels and interactable props, CoVR shows a high modularity through the scenarios it enables: CoVR is used in non-deterministic scenarios (between objects), and even anticipates the future user interactions within objects.

Finally, CoVR is robust and can embed large masses but also resist to body-scaled user actions; it is even strong enough to lead the users through forces and transport them. CoVR's implementation shows higher speeds than the other interfaces, but also a greater accuracy in its displacements. A technical evaluation in Chapter 6 also demonstrated that CoVR was safe around users, and fast and accurate enough to display physical objects prior to user interaction - which ensures its ease-of-use.

## 7.5 *"Haptics & Presence" Study*

The aim of this experiment is to estimate if CoVR enhances the sense of presence [Witmer and Singer, 1998]. During this experiment, we did not use our user intention algorithm but instead used a simple algorithm (CoVR has three target positions, which it chooses based on the user position), augmented with *visual effects* as a mitigation solution for speed and accuracy purposes (Chapter 4, Section 4.3.2).

*Participants and Apparatus.* 12 participants (3 female) aged 21 to 67 (mean = 29; std = 11) volunteered for this experiment and received a handful of candies for their participation. 8 participants had already used VR technologies, among them 5 were regular users. All participants played two implementations: a baseline and with CoVR. The order of experiments was evenly distributed among participants.

*Hardware.* All participants were wearing the HTC Vive HMD. Users also wore in-ears headphones and a noise-cancelling headset. For the baseline condition, users were introduced to the HTC Vive controllers and were taught to press its trigger to grab objects. Physical hands positions were extracted from the controllers' sensors to create virtual hand avatars in the game. For CoVR condition, participants were told they were entering a tangible world they could explore with bare hands.

*Virtual Scene.* The virtual scene, created with Unity3D, is illustrated on Figure 7.9-a[1]. It consists in one cube dispenser (-b) and two columns (-c), each with a basket on their top (-d) and multiple pathways (-e) to reach these columns. It also contains 4 virtual cubes (-a). In CoVR condition, the physical scene only contains one cube and one physical column. The physical column is assigned to both virtual columns and the cube dispenser. A slope under the basket brings the cube back to the *Cube dispenser* whenever it is dropped in.

[1] We would like to thank C. Rigaud for this scene design.

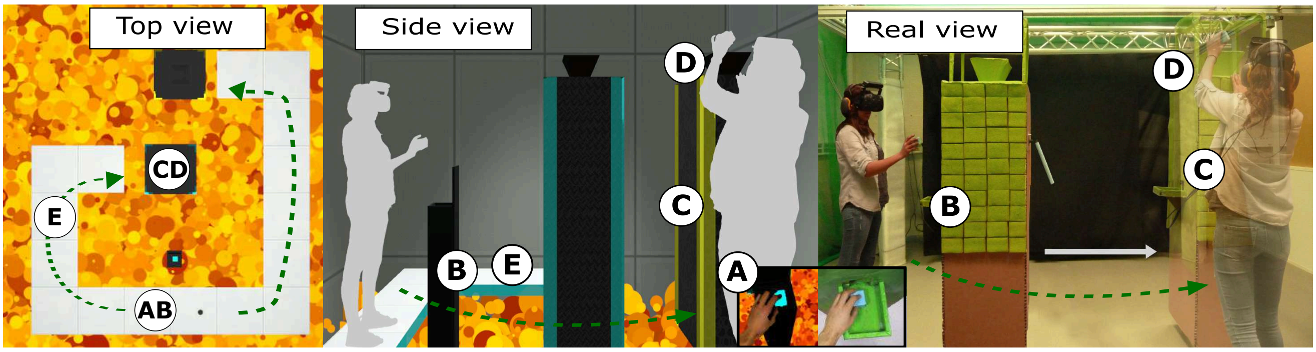



Figure 7.9: The virtual scene used in the experiment. Users pick a color cube (A) from the cube dispenser (B). They put it in the basket on the top of the column with the same color (C-D) by following the pathways (E). Otherwise the user falls down in the lava.

### *7.5.1 Experiment design*

*Task and Stimulus.* The task consisted of putting colored cubes in their respective baskets. Users had to perform the following scenario:

*Eve enters the virtual environment and is invited to wander around freely. A red cross appears at a corner of the room, which she has to reach. Whenever she does, a pathway appears, leading to the Cube dispenser. When she grabs her first cube, two columns with colored baskets on their top appear with their respective pathways. She then walks and puts her cube in the right basket. If she does not follow the tracks or drops the cube, she falls down in the virtual lava. Whenever she matches the right cube with the right basket, Eve gets a point. The game stops when Eve reaches 4 points.*

> This scenario has been designed for users to explore three of CoVR's interactions opportunities, based on Chapter 3. Indeed, users are invited to move in a large physical arena (*navigation*), to *explore* the tactile qualities of the columns and *manipulate* objects (cubes) to interact with other objects (baskets) with a $< Kvirtual : Nphysical >$ mapping.

*Procedure.* Before the experiment, the participants were asked to fill up an *Immersive tendency questionnaire* [Witmer and Singer, 1998] based on their personality, their past experience in VR and their current mood. The experimenter explained to the participants that they were going to play a VR game with two different setups: either with handhelds or bare-handed. No instructions was given about their walking speed but participants were invited to explore the virtual scenes without rushing or running, for safety concerns. The game designer randomly assigned each participant to one of the following group: BASELINE-CoVR or CoVR-BASELINE defining the order in which they were going to experiment the two conditions (Within design). In the Baseline condition, the experimenter asked participants to hold the Vive controllers in their hands and explained how to use them. In CoVR condition, participants were informed that they were going to interact with physical objects they had to grasp. Participants took a 2mn break between the two conditions, which gave enough time for the operators to install or remove the physical column.

During the experiment, participants were invited to think aloud and stop the experiment if they experienced motion sickness or felt uncomfortable. The duration of each game was about 6 minutes (no statistical difference between the two conditions). None of the participant derived so much from the scenario that it required human assistance.

After the experiment, they filled a presence questionnaire (see section Results) and answered to a semi-structured interview.

*Presence questionnaire.* The presence questionnaire is based on [Witmer and Singer, 1998][2]. The subscales are Involvement/Control, Naturalness, Interface quality; Auditory and Haptics, with questions for both conditions with a Likert scale from 1 to 7. As the original questionnaire did not focus on haptics, we decided to add the question *Were you involved by the tactile aspects of the environment?* in the subscale haptics. This question is similar to the original questions 5 (for vision) and 6 (for audio).

[2] This is the common questionnaire discussed in Chapter 2.

Even though the visual aspects enhance the involvement and control in the presence questionnaire, we decided to keep our results free from any personal choice to remain as close as possible to this normalized test. We used the question 4 *"How completely were all of your senses engaged"* in the Results chart (Figure 7.11), and decided to add a *Vision* subscale using the questions 5 and 14 to be able to compare accurately the auditory, touch and vision senses without blending them with the control/involvement subscales suggested by the questionnaire.

### 7.5.2 Pilot study

We conducted a pilot study with 6 participants to test our visual effects *mitigation solution*[3] when a *spatial mismatch* occurred: the animation (↓↑) consisted of the virtual column sinking in the lava (↓) when the physical column was away, and rising up again (↑) once the physical column was in-place.

[3] cf Chapter 4, Section 4.3.2.

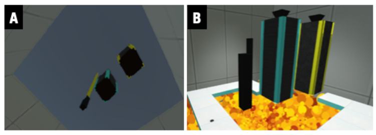



Figure 7.10: We inverted our visual effects thanks to the pilot study: (A). The column rose to the sky (↑) and lands back (↓). (B). The columns are back into place.

*Results.* We observed unanticipated behavior during the ↓↑ spatial mismatch animation. First, some users looked down to observe the column sinking. It resulted in the participants being too close to the target location of the physical column, preventing this latter to arrive. Second, some participants tried to intercept the column when the virtual one was rising back (↑) to put their cube in the basket during the motion. As the physical column was already in-place but invisible, the participant collided with it. We solved this problem by simply **inverting the animation**: the virtual column rises up to the sky to disappear (↑) (Figure 7.10 - A), and lands back when CoVR is in place (Figure 7.10 - B) (↓). This visual effect (↑↓) had a strong impact on users' behaviour: participants looked up and slightly stepped back to watch the disappearance, which was sufficient to let the real column arrive. It also prevented the basket to be accessible before the end of the animation.

### 7.5.3 Results

#### *Quantitative results*

The analysis of the data relies on 95% confidence intervals (CI), which we report visually in Figure 7.11.

*Senses.* Figure 7.11 summarizes the results regarding the three main senses involved in the experiment. As expected, we do not observe differences on visual (m = 6.46; CI = 0.29) and auditory (m = 4.22; CI = 0.66) immersion for both setups (Baseline and CoVR). However, our results suggest that CoVR (m = 6.0; CI = 0.48) outperforms Baseline (m = 4.5; CI = 0.75) regarding haptic immersion. Moreover, the results do not reveal significant differences between haptics (m = 6.0; CI = 0.48) and visual immersion for CoVR, with high scores for both of them ($> 6$).

*Overall virtual experience.* Our results do not reveal significant differences on

Involvement ($m_{CoVR} = 6.1$, $CI = 0.2$; $m_{Baseline} = 6.2$, $CI = 0.2$), Naturalness ($m_{CoVR} = 5.9$; $CI = 0.4$, $m_{Baseline} = 5.6$: $CI = 0.4$) and Interface quality ($m_{CoVR} = 4.0$; $CI = 0.7$, $m_{baseline} = 4.25$: $CI = 0.7$). While both Involvement and Naturalness are high (>5.5 out of 7), Interface quality is significantly lower ($< 4.5$ out of 7), mostly because the corresponding questions concern the control mechanisms how they interfere with the users' experience (controllers for Baseline or the depth matching of the hands for CoVR). The actions (grasping, releasing) were rated at 6.4/7 ($CI = 0.3$).

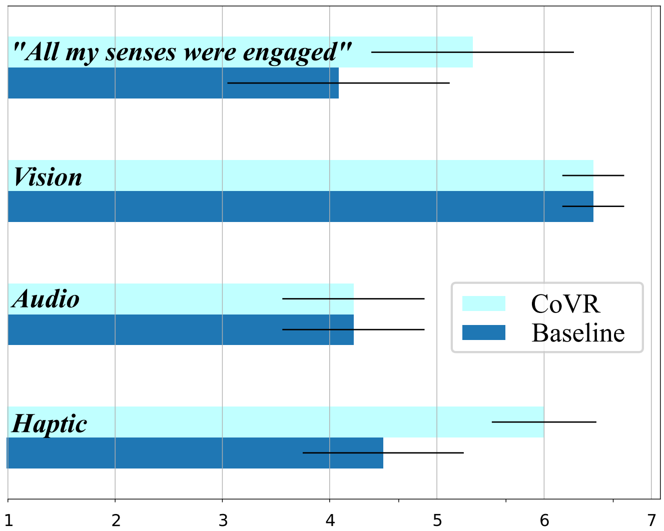



Figure 7.11: Summary of senses-related questions. Error bars indicate 95% Confidence interval

*Handles.* 83% (10/12) of the participants found bare-hand interactions (CoVR) funnier than controllers (Baseline; 17%; 2/12). From the ITQ, we found out these two participants were actually fond of video games. They finally reported this was why they preferred interacting with classic controllers.

The following results only concern the interaction with CoVR.

$< virtual : physical >$ *mapping.* 92% of the participants (11/12) thought there were 2 physical columns in the arena and 1 physical cube dispenser. Only one person understood the mechanism by thoroughly exploring the column tactilely. Moreover, all of the participants (100%) testified they had manipulated 4 cubes, when only a single one was in the real scene.

*Mechanics.* CoVR was robust enough during the experience as it did not require any operator intervention. Moreover, none of the participants heard motor noises when the column was moving. However, they all heard lasers and beeps from the game. Three participants reported hearing some embers[4], probably due to the lava beneath them.

[4] These ember noises were not implemented.

### *Observations and Interviews*

*Virtual experience.* All the users told us they found the environment interesting and that they feared falling down. The ones who dove in the lava felt amused by it, but were really careful afterwards. None of them tried to put the wrong cube in the wrong basket.

*Realistic experience.* Two of CoVR participants felt the basket game was so realistic they literally threw the cube in the basket from the cube dispenser position, and one even managed to score. Four participants thought the game was too short and wanted to play longer to keep exploring the environment thoroughly. Some reported feeling involved in the environment thanks to the touch of the column borders.

*Spatial mismatch.* The few participants who experienced spatial mismatch found the animation funny and believed it was part of the game. We observed that the column was fast enough against the walking speed of participants testing CoVR condition first. Spatial mismatch animations were mainly required by participants testing CoVR condition after BASELINE, probably because they were already familiar with the scene and proficient in their displacements. Finally, some participants reported visual mismatch between their hand representation and the virtual cube. Participants rated their "visuo-haptic match" with a 5.4 score ($CI = 0.85$). The reactions when touching the first real cube were *surprise* and *amusement*.

*Tactile Feedback.* One of the highlights was the different textures we implemented. A couple of users asked for more textures and objects to play with, and were curious to find out about new scenarios.

### *7.5.4 Discussion*

In this first "Haptics & Presence" study, we demonstrate as expected that CoVR enhanced presence through Haptics, against BASELINE condition (controllers). This column design provided a high level of haptic immersion (score $> 6$), despite DIY (low cost) objects and surfaces, at a comparable visual immersion level. In particular, the $< virtual : physical > mapping$ was successful as 92% of the participants (11/12) did not realized that they were interacting with a single cube and a single column.

Users enjoyed *navigating* in the arena, *exploring* textures, and *manipulating* physical props while being **unencumbered** from any contraption. The high quality of this haptic immersion enabled by interacting with real objects also raises new expectations from the participants. Two of the participants felt the basket game was so realistic they literally threw the physical cube into the basket from a far distance.

## 7.6 *Usability Study*

We created a two-scene demo application to demonstrate the interaction possibilities offered by CoVR - with more atypical interactions (eg involving CoVR's *dynamic* use). It relied on the 3-side column illustrated in Figure 7.12 and involved 5 interactions, 7 virtual objects but only 5 props. We use this demo application as our Usability study.

Figure 7.12: Illustration of the panels used in the demo applications.

As mentioned in Section 7.3, in this evaluation we are not interested in quantifying presence. The goal of this study is three-fold: (1) validating the implementation of CoVR, (2) investigating how users experience (i.e. apply and receive) strong forces and (3) collect feedback on the interactions of the demo applications.

*Participants.* 8 participants (4 male) aged from 22 to 30 (std = 2.8) volunteered to test the demo application. 4 of the participants were familiar with VR technologies, 2 had only tried VR once and the remaining 2 had never experienced VR.

*Hardware.* All participants were wearing an Oculus Rift S HMD as well as Optitrack markers on their dominant hand.

### 7.6.1 *Experiment Design*

*Procedure.* Participants were informed they were going to interact with physical props and were asked not to rush within the scene. They all were introduced to CoVR and saw it moving beforehand. A *game master* was present during all the experiments, to ensure the participants' safety and activate some of the interactions. After the experiment, participants filled a Likert-scale questionnaire about their enjoyment on each demo interaction and then participated in a semi-structured interview. They gave approximately 20 minutes of their time.

*Tasks and Stimulus.* In the following subsections, user interactions are displayed in **bold** while the motions and CoVR's interactions are displayed in *italics*.

#### *Escaping the Room*

We created a first scene where the users need to escape a room.

*Reaching for the Light* First, Bob is in a dark room where the only thing visible is a light bulb, at a 2.5m height, in a small cupboard. Bob hence **climbs** in the cupboard to touch the bulb, which then turns on the lights. In the physical world, he hence **goes into CoVR**, which *remains still* and touches the top of CoVR's skeleton.

*The Magic Wall* Bob then sees a carpet with the words "Start". Once he reaches it, three walls appear. A sign informs him he needs to push them. Bob chooses a wall, but can change his mind and pick another one if he wants. He then has to **maintain contact** and **keep pushing** for 10 seconds. The walls' color changes from green to red (accordingly with the timer), to indicate Bob he needs to keep pushing and that a maintained contact is needed.

When the walls appear, CoVR hence *uses the users' intentions-based algorithm* in order to place itself at the chosen wall. When Bob pushes a wall, CoVR remains *static*. Once the timer is finished, CoVR *steps backwards*, which gives Bob the impression of **having pushed the wall himself**.

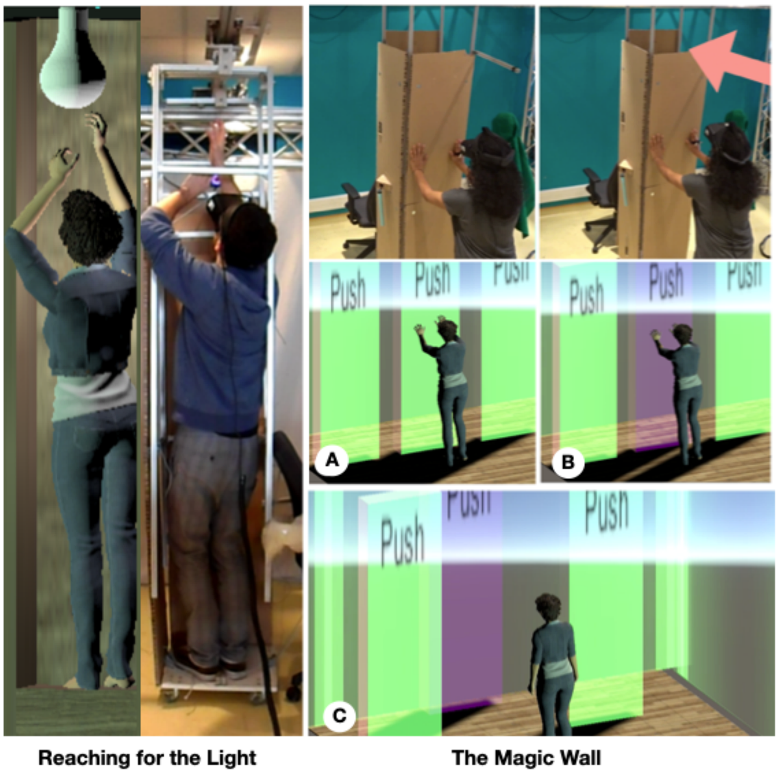



Figure 7.13: "Escaping the Room". *Reaching for the Light*: User climbs in the cupboard to reach the virtual light bulb; *The Magic Wall*: (A) User chooses a wall. CoVR moves accordingly with the user's intentions. User pushes on the wall. *We note that none of the users touched the "ghost" by accident during the experiment.* (B) The wall remains static, and changes color to encourage the user to maintain contact. (C) After 10seconds of maintained contact, the Magic Wall moves, giving the user the impression of having pushed it herself.

### *Travelling in the Clouds*

After pushing the walls, dust flies around Bob, who is then teleported in a forest.

*The Magic Broom* The user now sees a magic broom. He **holds** it tightly, and is now **pulled** by CoVR, through the forest to the clouds. CoVR *pulls the user* with a strong force-feedback, as the broom is actually a cylinder attached to CoVR with a string and a spring (see Figure 7.14 and Figure 7.2 - 1).

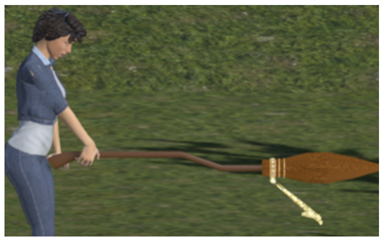


Figure 7.14: Avatar catching a magic broom.

*Moving in the Clouds* Once the travel is over, a "Continue" panel appears. When Bob touches it, a chair appears. Bob then **sits comfortably** in the chair, and CoVR *transports* him through the clouds.

Figure 7.15: *Moving in the Clouds*: User is sitting in a chair and physically transported through the clouds.

*The Ghosts* The user, in the clouds, is now surrounded by ghosts. He then sees a halo, in which he decides to go into. When he reaches it, he then sees a huge ghost about to go through him. Bob **remains still** while CoVR *initiates the interaction* by *brushing his head with a piece of fabric*.

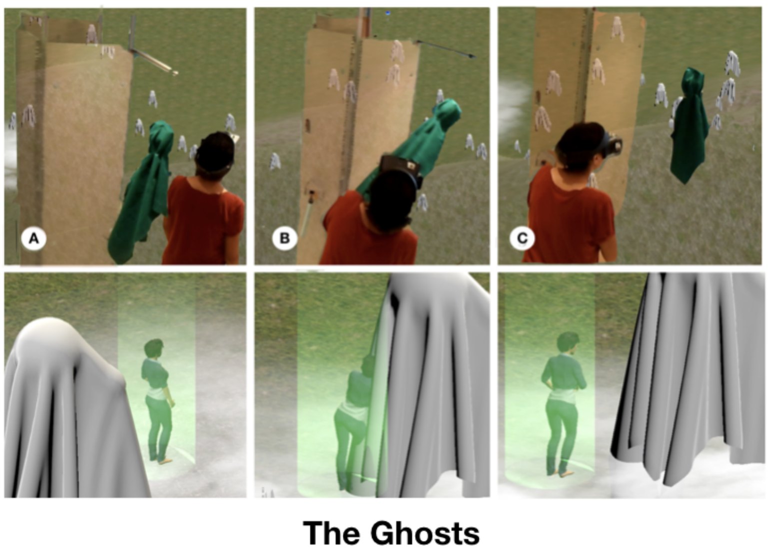



Figure 7.16: *The Ghosts*: (A) User enters the halo. (B) A piece of fabric lightly brushes the user's head. (C) The ghost flies away.

### 7.6.2 Results

#### Quantitative results

Participants ranked their global enjoyment with a 6.0/7 grade (std = 0.5).

*Favourite interactions.* Users were asked to choose their two favourite interactions in terms of enjoyment, among the five that were provided. 62.5% of the participants said their favourite interaction was the *transport*, while the remaining 37.5% preferred the *magic broom* (being pulled). The second favourite interactions were evenly split between *pushing walls, the magic broom, transport and being gone through by ghosts*.

*Force-feedback.* All of the participants ranked the force they applied (*wall*) or applied to them (*broom*) compared to their maximum force on a 7-point Likert scale (1 = pretty soft, 7 = very hard). The forces they applied to the walls was ranked with an average of 5.5 (std = 0.75, min = 5/7, max = 7/7) while the force applied to them with the magic broom was ranked with an average of 6.1 (std=0.64). In particular, 87.5% of the participants (7/8) ranked the force applied to them with travelling with the magic broom between 6 and 7/7 (the last participant attributed a 5/7 grade).

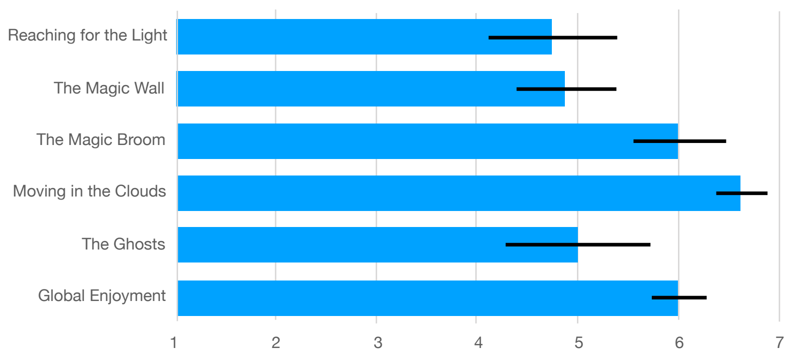



Figure 7.17: Enjoyment results per interaction, ranked on a 7-point Likert scale - 1 indicates "not enjoyable", 7 indicates "very enjoyable". Error bars indicate the standard deviation of the grades in the users' panel.

*Spatial Mismatches.* None of the participants experienced spatial mismatches, even with the non-deterministic scenario involving multiple doors.

*Apprehension.* The participants ranked their fear of being around a moving platform with a Likert scale (1 = not scary at all; 7 = frightening). The average fear was 3.6/7 (std = 1.5). P2 (expert VR user) told us that he would have liked to have noise cancelling ear-puffs and ranked his scare with a 6/7 grade, as the noise was keeping him from being fully immersed. All of the non-expert users ranked their scare with a 2 or 3/7 grade and dove into the VR environment without apprehension.

### *Qualitative results*

*Whole-body Interactions.* In our semi-structured interview, we discussed the users' game preferences. All of the participants told us that they prefer whole-body interactions in exploration games, where performances do no matter. They all informed us they enjoyed our game and the interactions it provided, and were mostly surprised to be pulled by the broom or transported.

*Force-feedback.* They were especially surprised by the force provided by the broom, as it was the first *dynamic* interaction they were experiencing. P5 said that she was afraid of heights in the virtual scene, so when the broom started pulling her, she felt quite stressed out. P4 told us she enjoyed manipulating real objects.

*Future Interactions Opportunities.* We asked participants to give us feedback on interactions they would like to experience in VR with CoVR. Two external expert users told us that they would enjoy climbing on a wall. P4 mentioned virtual escape game, where she could truly benefit from passive haptics, manipulate objects and feel force-feedback. P2 and P6 suggested war games, where they could lean on the walls to get some rest, or hide from enemies. P7 added he would enjoy having more modalities involved, for instance he would appreciate having a sensation of wind when climbing (on a stair or else) to increase his immersion.

### *7.6.3 Discussion*

We now summarize and discuss our main findings.

*Experiencing strong forces*. The experiment also revealed the benefits of robotic interfaces and more specifically *Encountered-type of Haptic devices* providing strong forces. Indeed, participants spontaneously applied 5.5/7 of their maximum forces when pushing on the walls. One participant reported having applied "very hard" forces (7/7). Moreover, participants perceived the strong (6.1/7) tension forces when interacting with the broom and enjoyed them (second favourite interaction, and an average of 6/7). Seven participants reported having received "very strong" forces (>6/7).

*Transporting the user*. The favourite interaction was "transport" (6.6/7) where a user was sitting on a chair moving in the VR arena. This interaction requires both a large arena and a robotic system able to displace heavy embedded masses, which are unique features of CoVR.

*CoVR implementation*. The experiment validated CoVR's design as it did not show any failure from the Conception phase (Chapter 4) during the experiences: Our *robotic system* applied or received strong forces by the participants without damage (*robustness*). Moreover none of the participants experienced collision (*safety*) or spatial mismatches (*speed and accuracy*) while they were freely walking in the entire room-scale arena thanks to our *trajectory generation* algorithm and more particularly our user-intention model.

In summary, this experiment revealed that whole-body interactions involving strong forces (applying forces, receiving forces or embedding heavy masses) are a promising direction for future Encountered-type of Haptic devices.

## *7.7 Conclusion*

In this chapter, we presented CoVR from the Interaction step of the Robotic Graphics scenario from Chapter 4. We demonstrated its interaction opportunities by relying on Chapter 3 and drew novel interaction techniques involving whole-body postures and large force-feedback.

We evaluated CoVR through the classic normalised *presence* questionnaire evoked in Chapter 2, and through the dimensions we depicted all along our Analytical Framework (Part I). We reported on a user study investigating how users experience haptic interactions with CoVR. It first validated the technical evaluation results, and compared the enjoyment over the different available interactions enabled by CoVR. This study emphasises the importance of enabling whole-body interactions and large kinesthetic feedback in VR, especially "being transported", which was the favourite interaction.

To summarize this second part of the dissertation, we presented CoVR, a Robotised Tangible User Interface providing Haptic feedback in Unencumbered VR. It anticipates intentions to physically encounter the users.

Hardware-wise, we showed CoVR was fast and accurate enough to physically overlay the users' objects of interest prior to interaction, and its trajectories naturally avoid users. It is robust enough to resist to body-scaled user actions and supports pulling the users through forces and even transporting them. Software-wise, it **predicts** which object of interest to overlay, and **where** the interaction will occur, within this object. Interaction-wise, its design space covers almost all of the "User Opportunities"[5] depicted from our Analytical Framework (Part I): fine bare-hands exploration and manipulation - through the use of passive props; whole-body involvement and postures - with large kinesthetic feedback. CoVR also offers novel interaction techniques, such as leading the user through forces or transport her.

[5] CoVR does not enable "Edition" yet. This will be discussed in our Future Work, Chapter 8.

> CoVR was presented at the CNRS $80^{th}$ birthday.
> It was chosen to be the first *federating project* in the ISIR laboratory. It is currently being augmented with a second column: we will describe these changes in our Short-Term perspectives (Chapter 8).

WHAT YOU MUST REMEMBER

*Contributions:*

- The exploration of CoVR, a system allowing whole-body interactions in a large workspace, with both static (manipulation, exploration) and dynamic scenarios (force-feedback leading the user, transportation), through rich tactile and kinesthetic feedback.
- Empirical results on the users presence and their most enjoyable scenarios using CoVR.

# Part III

# Conclusions and Perspectives

# 8

# Conclusion and Perspectives

Integrating Haptics in Virtual Reality aims to improve the interaction plausibility and believability. In these regards, I emphasize in this dissertation the importance of **Unencumbered Interactions in VR**, and demonstrate how the use of *Robotic Graphics* - also known as Encountered-type of Haptic Displays - leverages them.

Along this dissertation, I promote a triangular approach, distinguishing Haptics in VR through three categories: *Haptic Solution*, *Haptic Feedback*, and *Haptic Interaction Techniques*. I therefore use these three categories to explore the challenges and opportunities of Integrating Haptics in VR *(Chapter 2)*. I first provide an Analytical Framework *(Part I)*, which emphasizes the potential of Robotic Graphics interfaces *(Chapter 3)* and provides a groundwork for their conception, implementation and evaluation, through their current failure modes and their global specifications *(Chapter 4)*.

I build on this first part to introduce CoVR, as a conceptual Robotic Graphics interface - anticipating the users intentions to physically encounter them with their expected haptic feedback *(Part II)*. I then design, develop and evaluate CoVR. Software-wise, it predicts the users intentions both among many objects of interest *(Chapter 6)* but also within it *(Chapter 5)*; Hardware-wise, it displays acceptable safety, speed, accuracy and robustness, according to the Analytical Framework specifications *(Chapter 6)*. Interaction-wise, CoVR enables a wide set of currently available interactions, but also enables novel interaction techniques, mostly through the involvement of the whole-body and large force-feedback *(Chapter 7)*.

In this chapter, I summarize my findings and contributions and discuss the perspectives for short, medium and long term.

## *8.1 Progress on Research Problems*

This thesis is centered around enabling Unencumbered Interactions in VR with consistent haptic feedback. We discriminated this question through our triangular approach (Figure 8.1).

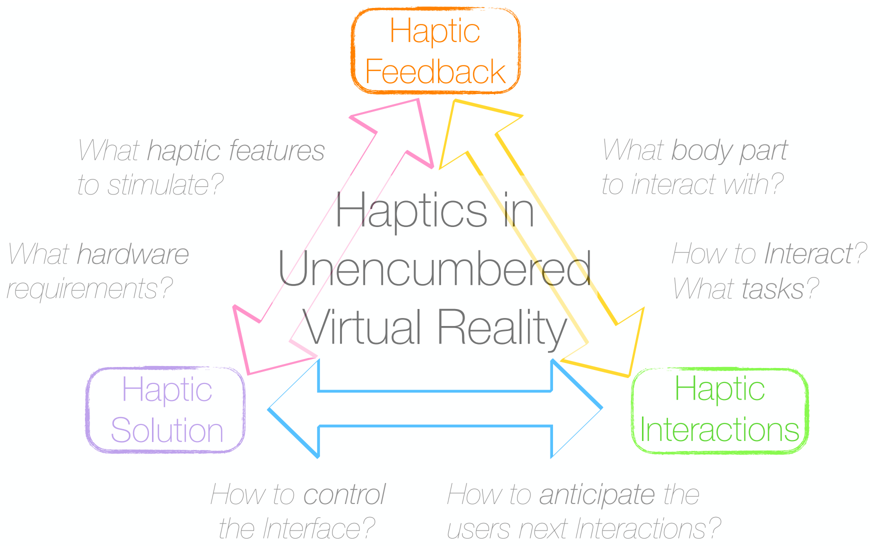



Figure 8.1: Original Triangular approach, Haptic Categories and associated questions.

In this dissertation, we derive our original research question through our three Haptic-oriented categories:

HAPTIC FEEDBACK How to provide users with both fine tactile and large kinesthetic feedback?

HAPTIC INTERACTION TECHNIQUES How to enable intuitive interaction techniques?

HAPTIC SOLUTION What the hardware requirements for such an interface?

In the subsequent subsections, we thus summarize our findings regarding these questions.

### *8.1.1* HAPTIC FEEDBACK

In order to provide fine tactile feedback, we opted for a simple solution: we exploit tactile properties (textures, shapes) from real props to overlay virtual haptic features (*Chapter 3*). Using real untethered props also enables to stimulate kinesthetic cues: they enable a complete haptic transparency and an adequate inertia. Yet, untethered objects are not sufficient to provide the users with the rigidity of a fixed wall for instance: enabling this expected perceived stiffness must then be realised through another method.

In these regards, we also focused on attaching props to a fixed and rigid structure, therefore providing the users with large kinesthetic feedback when they act on it (*static use of CoVR*). Kinesthetic cues were reciprocally stimulated by having the interface to act on users (*dynamic use of CoVR*). We empirically found that users enjoyed receiving large kinesthetic feedback but also the fine exploration and manipulation of untethered props (*Chapter 7*).

Defining *How* to provide users with tactile and kinesthetic feedback was translated in mechanical requirements: in order to display adequate inertias, perceived stiffness and haptic transparency, we defined that our interface should be robust enough to embed potential large masses and resist to body-scaled users actions (*Chapter 4*).

### *8.1.2* HAPTIC INTERACTION TECHNIQUES

Prior to defining *How* to enable intuitive interaction techniques, I first *defined* VR Interactions, their associated Techniques and Haptic Solutions (*Chapter 3*). We depicted five Interactions: *Navigation, Exploration, Manipulation, Edition, Whole-Body involvement*. We then took root from the *real world* interactions to better define their most intuitive associated techniques: *Real Walking, Real touch, Direct Manipulation, Physical Edition, Through postures*. Real world interactions also helped us to define novel types of interaction techniques, such as *Transportation* or *Being led through forces*. These interactions were empirically evaluated as the most enjoyable ones, and therefore show a promising potential.

Then, defining *How* to enable these interactions was the setpoint in our design process. We designed CoVR to encounter the users at their object of interest, while letting them unencumbered from any contraption. In order to perform these intuitive interactions, we focused on the design of User Intention Prediction Models, both within-objects (*Chapter 5*) and between-objects (*Chapter 6*). These predictions are key to enable unencumbered interactions: they provide their associated interface with a sufficient delay to encounter the user *prior* to interaction (*Chapter 4*).

### 8.1.3 HAPTIC SOLUTION

We first emphasized the potential of Robotic Graphics interfaces (*Chapter 3*), and then displayed the different conceptual and implementational challenges of Encountered-Type of Haptic Displays in *Chapter 4*: CoVR is required to be fast, accurate, and safe around users.

Moreover, the two past subsections also displayed some hardware requirements for our Interface, CoVR, *covering* virtual objects with physical ones:

- CoVR is robust, in order to provide a consistent Haptic feedback.
- CoVR works in a large VR arena, and enables intuitive interactions and their associated techniques by anticipating the users intentions, to encounter them *prior* to interaction.

We leaned towards the design of a room-scale grounded XY Cartesian robot. This design does not display technical complexity (only two degrees of freedom), and benefits from its grounding to ensure great speed and accuracy. CoVR was empirically validated performance-wise: it provides a safe user environment (no collision), is fast and accurate enough to alleviate the use of performance-related failure mitigation solutions (from *Chapter 4*), and is robust enough to resist to body-scaled user actions.

## 8.2 Scientific Contributions

The contributions of this work are *Methodological*, *Artefact* and *Empirical*.

- *Methodological Contributions*
  - *Analytical Framework.* I provided an analytical framework to analyse VR interactions via Haptic Solutions and emphasized the use of Robotic Graphics (robotised interfaces encountering the user), which showed the best potential for providing consistent haptic feedback and natural interactions in VR.
  - *Novel approach to analyse interfaces.* In the analytical framework, I also analysed Robotic Graphics interfaces by transposing a quality control process from industry product design (*FMEA*, Failure Modes and Effect Analysis) to research. It offered a better understanding of these interfaces conceptual and perceptual challenges, and highlighted solutions mitigating them.

  - *Novel dimensions to evaluate Haptics in VR.* I critically described the current protocols for evaluating Haptics in VR, and proposed various dimensions through my analytical framework as an alternative. I emphasized the use of my triangular approach (Haptic feedback, Haptic interaction techniques, and Haptic Solution) and the distinction between the user and the designer.

- *Artefact Contributions*

  - *Design and Development of a novel TUI.* I described CoVR - a robotised tangible user interface which enhances haptics in VR - through its conception, implementation and evaluation. CoVR lets the users unencumbered as it encounters them at their intended object of interest without requiring any held/worn contraption.

  - *Design and Development of Intention Prediction Models.* As part of CoVR, I designed two *software bricks* for Robotic Graphics interfaces: they provide a safe model to control these interfaces, and two users intention prediction models at different scales - *within* the object of interest and *between* objects of interest). Predicting the users intentions enables to better anticipate *how and where to* encounter the user prior to interaction. These software bricks can be adjusted to other Robotic Graphics interfaces.

  - *Design of novel Interaction Techniques.* I drew novel interaction techniques in VR using CoVR, for instance involving large force-feedback, transport and whole-body postures.

- *Empirical Contributions*

  - *Technical Validation of CoVR.* I empirically evaluated CoVR's intention models with various simulations, verifying their validity.

  - *Perceptual Studies.* I empirically evaluated CoVR's interaction techniques, both qualitatively and quantitatively.

## *8.3 Perspectives and Opportunities*

In this thesis, I promote the use of CoVR, a Robotised Tangible User Interface for Unencumbered Interactions in VR. CoVR is a Robotic Graphics interface, which limitations I discussed in our Analytical Framework (*Part I)*. In this section, I describe the Short, Medium and Long-term perspectives and opportunities.

### 8.3.1 Short and Medium Term Perspectives

– *Evaluation of our Analytical Framework.* I first propose to use my Analytical Framework (*Part I*) to systematically evaluate ETHD interfaces, and more globally, novel interaction techniques and/or Haptic Solutions in VR (eg using our proposed Table, in *Chapter 3*). It exposed global directions to follow in order to evaluate *Haptics in VR* via *Haptic Solutions*. Comparisons and evaluations can then be summarized in an online database such as Haptipedia [Seifi et al., 2019]. We can then gather feedback from Haptics, Robotics and HCI experts to evaluate our framework usability, using surveys and focus groups.

Figure 8.2: 3D Printed Physical totems of various sizes.

– *Empirical Validation of Within-Object Intention Model with Physical Props.* As a second short-term perspective, I coupled the Within-Objects intention model from *Chapter 5* with a redirection model. I plan to evaluate it with physical totems (extracted from [de Tinguy et al., 2019]) of different sizes (Figure 8.2), to physically overlay complex shaped virtual objects. I also plan to evaluate the effects and discrepancies of a redirection *over each finger*, compared to a global hand redirection. As I mentioned it in *Chapter 5*, we can also evaluate resizing grasps [Bergström et al., 2019] with haptic feedback, using redirection and pseudo-haptic techniques with physical props.

– *Augmenting CoVR.* As mentioned by McNeely, Robotic Shape Displays such as CoVR are limited to the number of available props (*Chapter 4*). A short-to-medium-term perspective is to augment CoVR with various I/O capabilities. While CoVR's original approach focused on 2 degrees of freedom (focused on the interface displacement), additional capabilities could improve user experience. We could augment a column with internal degrees of freedom, a robotic arm to hand out some props - or to integrate more sensors (e.g. touch input, force sensors, proximity sensors, etc.). CoVR can ultimately integrate the undermentioned Shape-changing interface (Figure 8.3).

> In these regards, the second version of CoVR (evoked in *Chapter 7*) contains a rotation around the vertical axis. Beyond the additional degrees of freedom, we can also expand haptic stimuli to vibrations, sliding, textures, temperatures (for instance, heat-lamps or fans can be easily integrated).

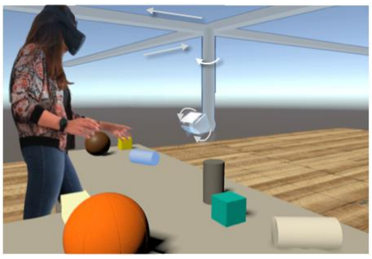


Figure 8.3: CoVR can be augmented with additional degrees of freedom; it can reconfigure itself to simulate objects of interest.

– *Design of a Shape-Changing Interface enabling Edition tasks.* I plan to design an encountered-type of shape-changing device that user could freely manipulate with both power and precision grasps, both uni- and bi-manually. I started prototyping a reconfigurable interface to attach on CoVR: it is composed of multiple servomotors, which orient its surfaces (see Figure 8.4). A short-to-medium-term perspective is to couple our mechanical design with our Within-

Object Intention model. The target is to display a correct surface orientation on each user finger. CoVR's body already cares for displacements, and I believe we can limit our interface available surfaces by adding a rotation on CoVR's vertical axis. I would like this interface to ultimately enable the *Edition* task that is currently lacking from Haptic Solutions in VR. Haptic Feedback-wise, it can also potentially enable the perception of *compliance*. This can extend the use of Haptics in VR for CAD design.

– *Improving CoVR's Usability and Modularity*. I mentioned in Chapter 3 how tracking could be an issue: it also requires all of the untethered objects to be augmented with markers (which can be potentially unexpectedly touched by the users). Adding a depth camera could enable the detection of untracked moving bodies, such as an unexpected pet in the VR arena, but also couple Computer Vision algorithm with Machine Learning algorithms to recognize the available objects within the scene. This technique is currently used to extract the users' hands in the Oculus Quest - used in *Chapter 5*, and could be extended to all of the virtual objects in the arena. Moreover, as I demonstrated in *Chapter 5* and *Chapter 6* how we could collect user data to perform simulations and improve our interfaces/models performances, I believe we can record the users' data to run ML algorithms and refine the users intention prediction algorithms. This ML integration can improve the user intention prediction model *within-objects*, with potential additional outputs, such as the prediction of grasp types (and consequently the number of future contact points). Refining this model can help with the design of the Augmented CoVR (mentioned above) as a medium-term perspective.

– *More Columns, More Robots*. One limitation of my approach is to only have of a single robot. Other ones can be mounted on the sides of the VR arena to control horizontal columns. Another idea consists in adding a second ceiling robot. Its work-area would be limited by the current position of the other robot. However, with an appropriate control strategy, it would be possible for each column to be on a side of the user, optimising trajectories and considerably augmenting interaction possibilities. We also envision a VR arena combining CoVR with a swarm of mobile robots such as [Suzuki et al., 2020]. These ones can collect objects on the ground and bring them back to CoVR. Our CoVR's trajectory generation algorithm remains valid in such configurations.

> The future version of CoVR as *ISIR's Federating Project* already envisions the integration a second column.

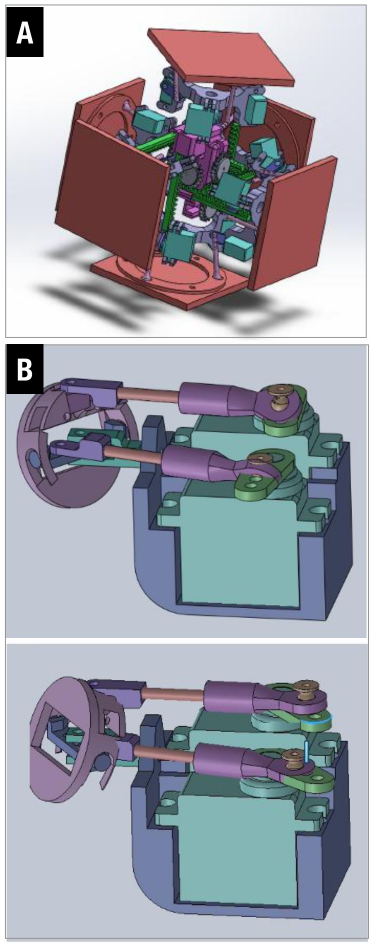



Figure 8.4: First design iterations for Shape-Changing Interface. (A) Six movable surfaces with 3-DoF. (B) Focus on a simpler design of One Movable surface with two servomotors.

### 8.3.2 Long Term Perspectives

- *Collaboration*. CoVR is currently designed for a single user interaction. From a software point of view, it can easily be updated to support several users in the same arena, each user considered as an obstacle. However, it is more likely that spatial mismatches will occur as the column can not be at two locations at the time. I plan to investigate which scenarios (e.g. a master and a slave) and which interactions would support collaborative interaction in a single arena. We can investigate remote-presence possibilities. A second identical structure can for instance be assembled in another room. Users in each room can interact with different OOIs, share mutual physical contact or collaboratively manipulate objects [Brave et al., 1998, He et al., 2017].

- *Design of a Lightweight Portable Unencumbered Haptic Interface*. CoVR is designed for room-scale VR arenas and can be used for Arcade gaming or Industry training. Yet, while the use of passive props is efficient for the current use-cases, we believe that a lighter interface, focusing on the stimulation of Haptic Features, can be more proficient for the expansion of at-home Virtual reality.
  The challenge will be to preserve *Unencumbered Interactions* and various *Interaction Opportunities* with a lightweight desktop/living-room integration. This raises questions Haptic Solution-wise, with the design and development of a novel robotised interface; Haptic Interaction techniques-wise, with the evaluation of required tasks (eg exploration, manipulation, edition); Haptic Feedback-wise, with the integration and evaluation of novel haptic stimuli (eg simulating textures, shapes, forces, weight, temperature). My framework can potentially be exploited to provide guidelines to evaluate this novel interface. To some extent - and because of the expansion of bare-hands interactions (such as with the Oculus Quest, which extracts and exploits the users' real hands) - this analytical framework could be used for the creation of a normalised questionnaire, exploring Unencumbered Interactions and their associated solutions n VR.

- *ETHD in Augmented Realities*. As previously mentioned, Virtual reality is expanding to various fields; in the same regards, Augmented Reality shows a promising potential. The challenge behind integrating Haptics in AR remains in the users perceiving their vicinity. Therefore, having a movable Encountered-Type of Haptic Display around the user can be disturbing. I mentioned in the *Short-Term perspectives* above that we can integrate Machine Learning and Computer Vision algorithms to improve models/interfaces performances. These can be potentially used to locate the ETHD interface, and to hide its displacements within the Augmented Reality environment. The global aim behind this long-term perspective is to adapt Unencumbered Interactions with Consistent Haptic Feedback to other Virtual Environment approaches (from *Chapter 2*).

## *8.4 Conclusion*

This thesis contributes to the paradigm of Unencumbered Interactions with Haptic Feedback in Virtual Reality. It promotes, in these regards, the use of Encountered-type of Haptic Displays, and shows the Conception, Implementation and Evaluation of CoVR, a Robotised Tangible User Interface.
Unencumbered Interactions were mentioned since the 90s as a Utopian goal for Virtual Reality, and I believe they should be envisioned to facilitate and amplify the deployment of Virtual Reality, and ultimately extend its usability.

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